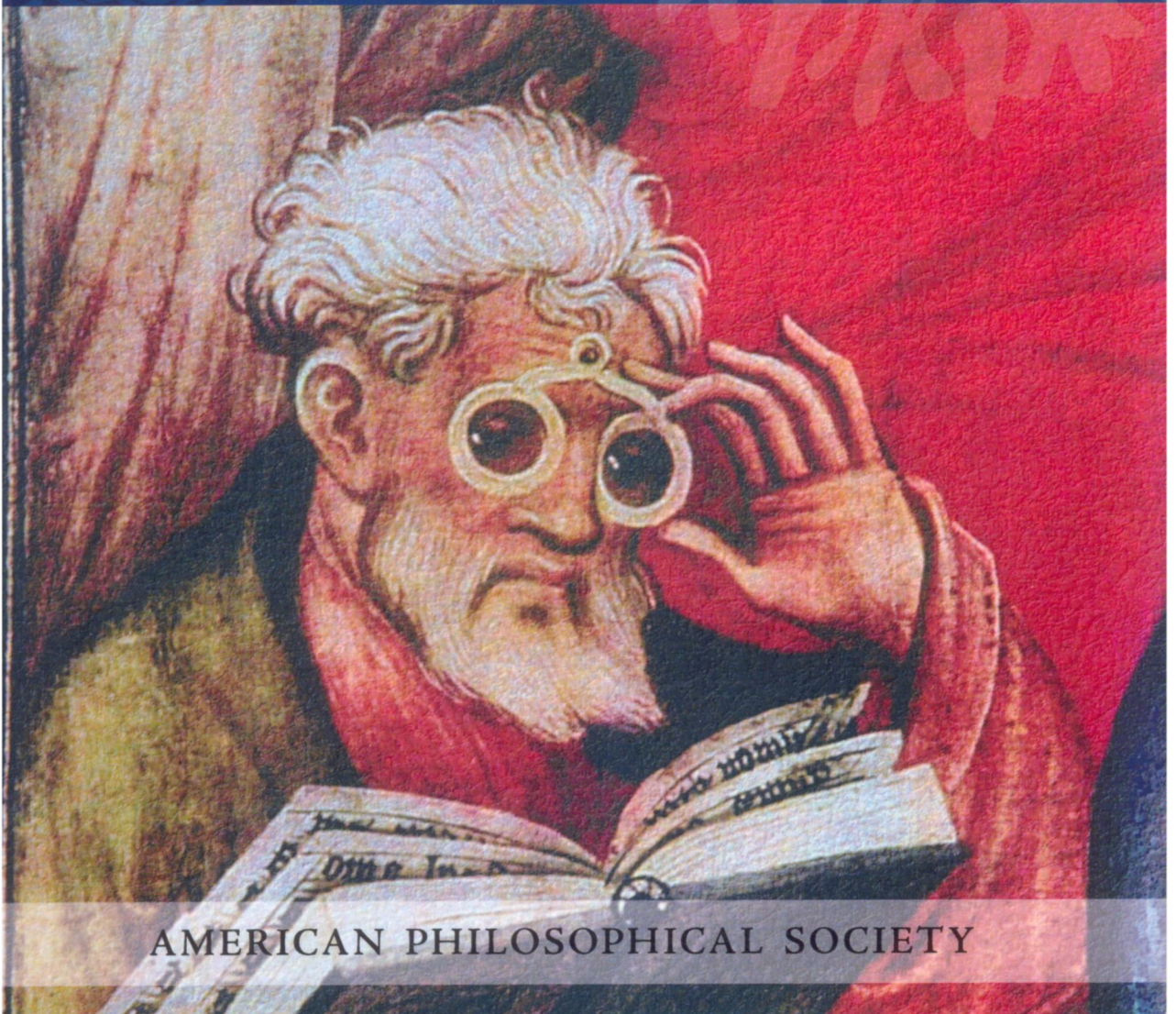


The Long Route to the Invention of the Telescope

ROLF WILLACH



AMERICAN PHILOSOPHICAL SOCIETY

The Long Route
to the Invention of
the Telescope



*The Long Route
to the Invention of
the Telescope*

Rolf Willach



AMERICAN PHILOSOPHICAL SOCIETY ♦ PHILADELPHIA ♦ 2008

Copyright © 2008 by the American Philosophical Society for its Transactions series, volume 98, part 5. All rights reserved.

Text and cover designed by Ellen H. Graben.
Set in Jensen with Historical English Textura display
by Graphic Composition, Inc., Bogart, Georgia.
Printed and bound in the United States of America.

ISBN-13: 978-1-60618-985-6

LIBRARY OF CONGRESS CATALOGING-IN-PUBLICATION DATA

Willach, Rolf, 1937–

The long route to the invention of the telescope / Rolf Willach.

p. cm. — (Transactions of the American Philosophical Society held at Philadelphia for promoting useful knowledge ; v. 98, pt. 5)

Includes bibliographical references and index.

ISBN 978-1-60618-985-6

1. Telescopes—History. 2. Lenses—History. 3. Eyeglasses—History. I. Title.

QB88.W53 2008

681'.412309—dc22

2008035637

FRONT COVER IMAGE: "*Brillenapostel*" ("Apostle with spectacles"), a portion of the altarpiece painting (1403) by Konrad von Soest in the *Stadtkirche* at Bad Wildungen, Germany.
See also figure 26, page 43.

BACK COVER IMAGE: St. Peter reading with spectacles. Detail from the altarpiece painting (1466) by Friedrich Herlin in St. Jacob's Church, Rothenburg ob der Tauber, Germany.
See also figure 24, page 41.

Transactions of the American Philosophical Society
Held at Philadelphia for Promoting Useful Knowledge,
Volume 98, Part 5





Contents

Foreword by Albert van Helden ♦ vii

Introduction ♦ ix

CHAPTER 1 *The Critical Issue* ♦ 1

What is a telescope?

CHAPTER 2 *The Technology of Grinding Crystals in Antiquity
and the Middle Ages* ♦ 4

The Nimrud Lens • *The Lothar Crystal*

CHAPTER 3 *The Reading Stones (lapides ad legendum)* ♦ 10

CHAPTER 4 *The First Dioptrical Vision Aids* ♦ 15

Hypothesis

CHAPTER 5 *Glass Techniques in the Middle Ages and
the Invention of Spectacles* ♦ 29

The schedula of Theophilus • *Glassblowing and glass grinding
in Venice in the thirteenth century* • *The effect of melting-point
reducers* • *The secret of firebrick* • *A Venetian trade regulation
of the year 1284 concerning crystal-glass craftsmen* • *The last
step* • *Rivet spectacles from the monasteries of Wienhausen and
Isenhagen* • *The difference in optical operation between a spectacle
glass and a telescope objective* • *Discussion of examination results*

CHAPTER 6 *The Development of Spectacles in the Later Middle
Ages and in the Renaissance* ♦ 56

The first negative spectacles • *Spectacle-glass production in northern
Italy* • *The influence of the invention of book printing upon the
development of spectacles*

CONTENTS

CHAPTER 7	Evolution of the Modern Lens-Grinding Technique in the Sixteenth Century + 70 <i>The dating of the spectacles • Improvements in lens-grinding techniques in the sixteenth century • Lens-grinding techniques in sixteenth-century Italy • Negative lenses in the sixteenth century</i>
CHAPTER 8	Written Sources of the Sixteenth Century Concerning the Combination of Two Spectacle Glasses + 85
CHAPTER 9	The Events in Holland in the Autumn of 1608 + 90
CHAPTER 10	The Breakthrough + 93
CHAPTER 11	Who Is the Inventor of the Telescope? + 93
CHAPTER 12	Summary + 100 <i>Antiquity • Early Middle Ages • High Middle Ages • The time of the Crusades (twelfth and thirteenth centuries) • The invention of cristallum in Venice (about 1280) • The invention of spectacles in Venice (about 1285) • Negative lenses for myopic eyes made in the sphere-blowing technique • The invention of lens grinding in concave molds • Negative lenses by the mold-grinding technique • The discovery of the magnifying effect of convenient combinations of two lenses • The invention of the telescope</i> <i>Acknowledgments + 105</i> <i>Notes + 107</i> <i>Further Reading + 111</i> <i>About the Author + 115</i>



Foreword

THE HISTORY OF SCIENCE is neither just the history of ideas, nor of laboratory practice, nor of social context. Among its other focal points is the craft tradition, from the prehistoric quartz flake to the strings and ceiling wax in J. J. Thompson's laboratory and beyond. But the craft tradition is often difficult to catalogue because artisans have in general handed down their skills orally, and rarely in writing. We have little beyond the surviving products of their craft. The study of these objects was an antiquarian occupation for much of the twentieth century, but in recent decades it has become an integral part of mainline research in the history of science.

In the case of the telescope, its history has been well illuminated for generations, but its *prehistory* has remained somewhat of a mystery until very recently. Its origins clearly lie in eyeglasses, but too little was known about their history, especially in the Renaissance. In his book *Renaissance Vision, from Spectacles to Telescopes*, Vincent Ilardi gives a massive inventory of early spectacles and considerable insight into the industry of spectacle-making. In his many articles, Sven Dupré has illuminated the research context of practical optics in the sixteenth century, while in her recent book, *Galileo's Glassworks*, Eileen Reeves has shed light on the social and political context of optics during this period.

As for the invention of the telescope, research has involved, for the most part, investigation of written sources, although technical considerations have lately crept in. There remained this conundrum: after the telescope became known in 1608–1609, a number of people in widely separate locations claimed that they had such a device long before the announcement came from The Hague; in the summer of 1608, no one had a telescope, in the summer of 1609, everyone had one.

For a number of years, Rolf Willach, an optical engineer by profession, has quietly tested early spectacle lenses in museums and private

FOREWORD

collections, and he now reports on this study, which gives an entirely new explanation of the invention of the telescope and solves the conundrum mentioned above. It leaves a smaller question at the end, but I will not give the plot away. Read and enjoy.

Albert van Helden
De Bilt, July 2008



Introduction

THE DEVELOPMENT OF THE TELESCOPE follows a long path over many centuries, beginning with the magnifying lens in its simplest design. These were rock-crystals (clear quartz) that were mainly produced for embellishment and decoration. Examples from Antiquity through the High Middle Ages will be examined to reveal the technology of their manufacture. From these earliest times different manufacturing techniques developed, beginning with the grinding and polishing of crystals for liturgical art and crafts in the workshops of monasteries, and ending with the invention of spectacles. After discussion of the development of spectacle lenses and the method used for grinding and polishing, we will cover the period from the early fourteenth century to the seventeenth century and will illustrate our argument with a number of examples. It will also become clear that the invention of the telescope was made possible only by practical experiments, chance discoveries, and an intensive interaction with the prevailing cultural and political changes in Europe.



The Critical Issue

THE TELESCOPE AND THE MICROSCOPE are inventions that have provided humankind with important scientific knowledge leading to significant advancements in our culture. It is therefore astonishing that their invention remains something of an enigma. Even to this day, their first appearance is subject to controversy.

Before we discuss this difficult problem, we have to define the telescope itself. This definition is far from self-evident. The simple physical description, namely that a telescope is an afocal optical system, is for our purposes completely useless. It silently presupposes that the lenses fulfill in their focal point a minimum condition of resolution for faraway objects. This was not, however, the purpose it fulfilled in earlier times. The development of the lens through the centuries, until the moment when this minimum condition could be satisfied, is the subject of this monograph.

What is a telescope?

A telescope may be defined as an optical system whose resolution of distant objects is superior to what one would see with the naked eye.

In this definition we find no hint of the construction of that instrument: the emphasis falls solely upon the crucial issue of improved resolution. Therefore, an optical device that enlarges distant objects without providing a clearer image of their details is not a telescope, even if its construction is exactly the same. The invention of the telescope is thus mainly a technological problem and not a theoretical one. Nothing in the

theoretical descriptions of optics in the preceding centuries refers to the possibility of such an instrument.

Optical examinations of the earliest surviving telescopes clearly indicate that the lenses of all these instruments are of spectacle glass. Therefore, one key to the solution of this enigma is greater understanding of the evolution of lens-making between the fourteenth and sixteenth centuries. The first mention of spectacles appeared in two manuscripts of the early fourteenth century. The oldest is preserved in the *Biblioteca Medicea Laurenziana* in Florence, under the shelf mark *Ashburnham 533*. It is a sermon of the Dominican monk Giordano da Rivalto, from February 23, 1305, made in the church Santa Maria Novella in Florence:

It is not yet twenty years since the discovery of the art of making eyeglasses for good vision, one of the best and most necessary arts that the world has.¹

Another extant document is a chronicle preserved in the Dominican monastery of Santa Caterina in Pisa.² The earliest entry dates from the early fourteenth century, and ends approximately one hundred years later. This chronicle was written by four different writers. In an entry for the year 1313 it reads:

... there lived and died a Friar Alessandro Spina, a monk of most excellent character and most acute mind, who understood everything whatsoever that had been made. When he saw something with his own eyes, he, too, knew how to make it; and when it happened that somebody else was the first to invent eyeglasses and was unwilling to communicate the invention to others, all by himself he made them and good naturedly shared them with everybody.³

Therefore the first appearance of eyeglasses can be dated to 1285–1290. Even knowing this rather precise date does not solve the highly speculative question of how the invention of spectacles was possible at this early point in our history. As the history of science clearly indicates, all discoveries, every invention, and all technological improvements are built upon a solid base of previous knowledge and experience. But it seems that evi-

dence for any previous knowledge base is still unknown for the spectacles that appeared in Northern Italy in the late thirteenth century. Until now, for lack of a better explanation, it has been said that lens grinders found the necessary knowledge in the books of Alhazen.

But despite several improvements in comparison to Euclid, in not a single passage in the seven books of *Opticae thesaurus* is there the faintest hint that might have suggested to glassmakers the idea of grinding pairs of identical convex glass lenses, with a refracting power of 2 to 4 diopters. An indispensable condition of such an invention only by theoretical reflections would be minimal, but correct understanding of the optical functioning of the human eye was essential. But to our knowledge, this important information was first developed by Johannes Kepler in 1604.⁴ In the thirteenth century no one would have imagined looking for the solution to the serious problem of presbyopia in optics. On the contrary, the *weakness of old eyes* seemed to be a medical problem, not an optical one, and improvements and relief were sought in remedies and tinctures. We also do not have the faintest indication that in the second half of the thirteenth century, a lens-grinding technology of the requisite accuracy existed.

To understand the invention of spectacles, therefore, we have first to solve the following problems:

1. Weakness of the eyes in older people was considered to be a medical—and not an optical—problem.
2. The optical principle of the human eye was wholly unknown.
3. The problem of the necessary quality in glass manufacturing was unsolved.
4. There was no technology available to grind and polish lenses of the required precision, much less in identical pairs.

The historical context of the invention of eyeglasses seems to be even more difficult to establish than that of the invention of the telescope. The latter instrument had the necessary components, and although they were imperfect, they did exist. This fascinating mystery in the history of science cannot be looked upon as resolved, until logical answers to these four issues have been found.



The Technology of Grinding Crystals in Antiquity and the Middle Ages

The Nimrud Lens

In 1853 the English archaeologist Henry Layard found an oval-shaped rock-crystal plate during his excavations in the ruins of the Assyrian town, Nineveh, in the northwest part of the palace on the hill called Nimrud. The artifact, found in a cultural layer from the period 900–700 B.C., was described in two different publications.^{5,6} (figure 1, British Museum Inv. No. 12091). Since both surfaces of the plate were slightly convex, it was called a *lens*. Upon examining this plate, the Scottish inventor and historian Sir David Brewster found a focal length of 4.5". More recently the Assyriologist Giovanni Pettinato has suggested that the plate was possibly the objective lens of a telescope, with which the Assyrians observed the moons of Jupiter and the rings of Saturn. To shed light on these hypotheses, I decided to conduct a careful examination of this crystal plate.

Geometry of the surfaces of the Nimrud Lens

The curvature of both surfaces of the Nimrud Lens was measured with a coordinate measuring device.

The results are shown in figure 2 for two cross sections, A–B and C–D. The y-axis is enlarged 2.5 times compared to the x-axis. The more convex surface is nearly plane (flat) on top. The different zones also have different and irregularly distributed curvatures in the range of 80 mm to 400 mm. The less convex surface is, by contrast, much more regular. As a result of the very irregular convex surface, the plate does not have a real

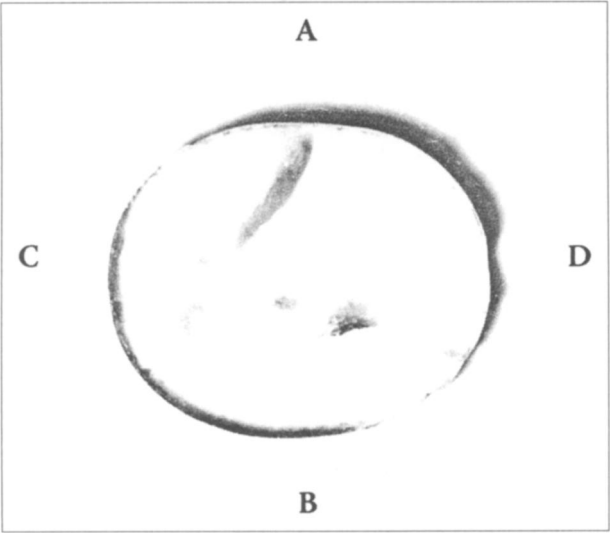


FIGURE 1.
The so-called
Nimrud Lens.
British Museum,
Inv. No. 12091, about
900–700 B.C.

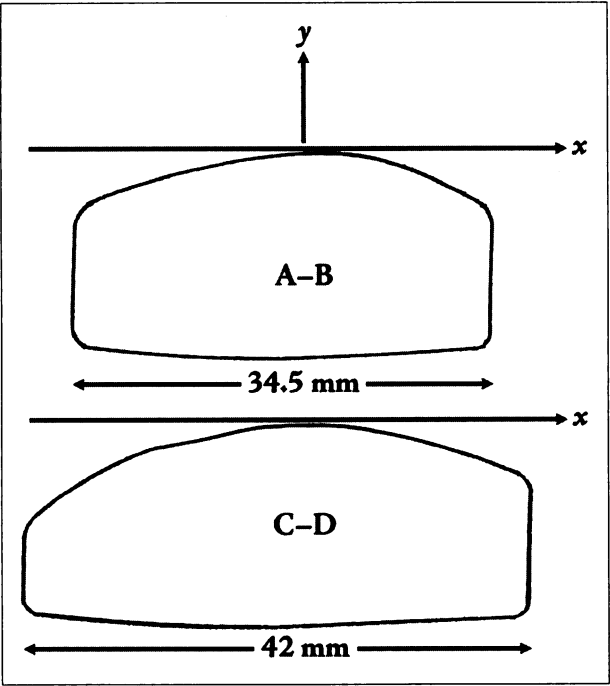


FIGURE 2.
Cross sections of the
Nimrud Lens with the
y-axis magnified 2.5
times to the x-axis.

focus. Along a diffused faint light line of many meters, there are different brighter concentrations. The brightest one is seen at a distance of approximately 110 mm. It may have possibly been the reason that Brewster attributed a *focal length* of 4.5" to this plate. Regardless of the irregularities, the plate has a more or less clearly recognizable rotational symmetry.

Grinding and polishing

An examination with a stereomicroscope indicates clearly that the grinding of the Nimrud Lens was extremely rough. Numerous scratches, running in all directions, cover both surfaces so that the transparency of the plate is seriously reduced. It is easy to see that the edges of all the scratches are polished. The scratches are therefore the result of an insufficiently fine grinding, and not of another subsequent influence.

Conclusions

The resulting inference—that this rock-crystal plate is not a lens and is certainly not a telescope objective—is in no way a surprise to the author. Nonetheless, the development of the rotational symmetry of the plate is of great significance. It indicates that the object was ground on a rotating surface, probably a plane copper or iron plate. The simplest rotating device, the potter's wheel, was already known in Neolithic times. The realization that grinding on a rotating plane surface, with the use of a grinding medium, was already well known in Antiquity is of the utmost importance to our subsequent investigations.

The Lothar Crystal

The Lothar Crystal (figure 3, British Museum Inv. No. 1855, 12–1.5), is a large, biconvex ground glass composed of very clear, transparent rock-crystal. It was made in the Carolingian period, around A.D. 855–869 in Metz, France, and was mounted in the fifteenth century in a frame of gilded copper plate. On the nearly plane posterior face we see a cycle of engraved figures that represent eight scenes from the life of the Biblical heroine Susanna. The figures, approximately 20 mm in height, were engraved with great skill using a diamond tool. Above the circle in the central part an inscription confirms that this crystal was made for the Carolingian King Lothar II. Due to its grinding and polishing quality, as

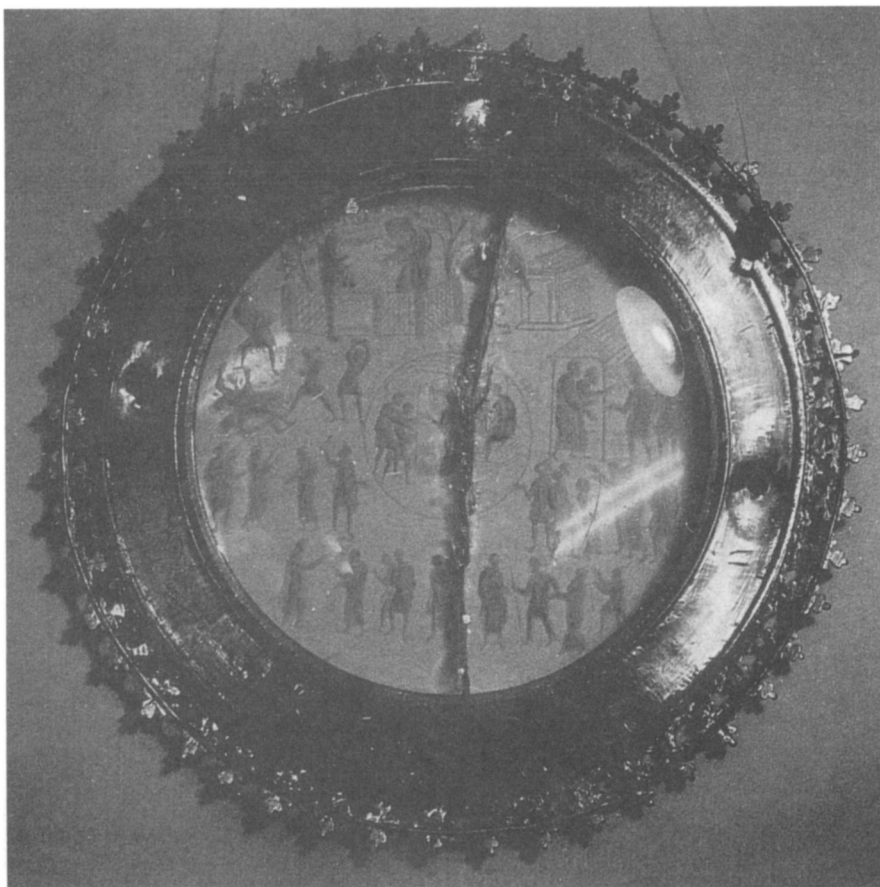


FIGURE 3. The Lothar Crystal. British Museum, Inv. No. 1855, 12–1.5. Metz (France), about 855–869.

well as to the beauty of the engraved figures, the Lothar Crystal is one of the most highly valued pieces of medieval art. It is well known that the crystal has been in the possession of the abbey Waulsort (Belgium) since the late tenth century. In 1793, during the turmoil of the French Revolution, troops plundered the monastery. The monks threw the precious piece into the Meuse River, where it was later recovered with a crack through the center of the lens.

The front surface is aspherically convex, and the whole piece is therefore a lens with faint magnification. Figure 4 shows the lines of constant refracting power. The clearly visible asphericity indicates that this lens was ground on a rotating plate. The high degree of rotational symmetry is

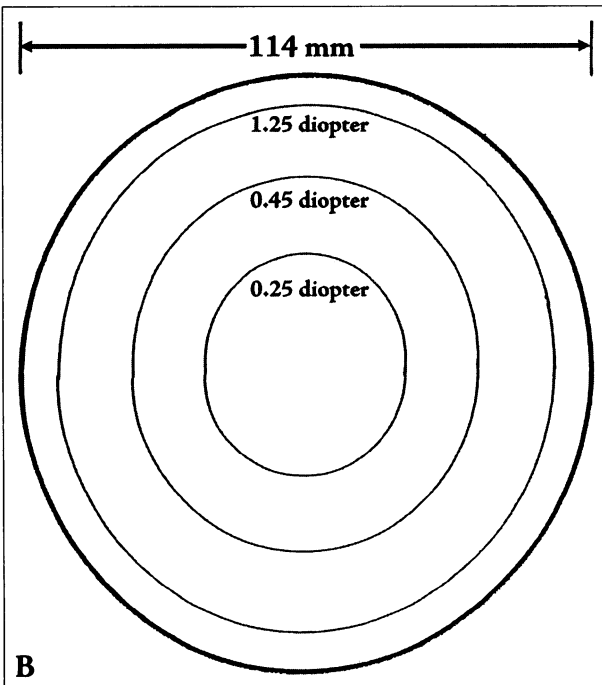
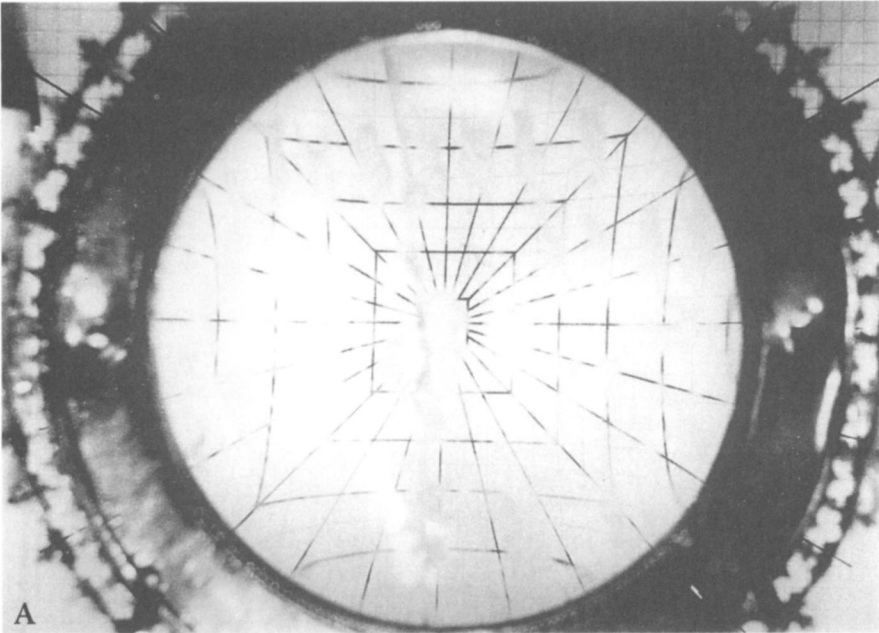


FIGURE 4.
Test image (above)
as seen through
the Lothar Crystal,
and lines of equal
refracting power
(left).

astonishing, as we can see in figure 4A, which represents a test figure held at the rear of the lens at a distance of 5 mm.

In the Nimrud Lens and in the Lothar Crystal we recognize that important elements of grinding—elements still in use in the twentieth century—were already well known to the Assyrians and to European monks in the ninth century. These important elements included:

1. A hard grinding medium. In the Orient and in Italy hard emery (corundum = Al_2O_3), which is found in the whole region, but especially on the Greek isles (Naxos), and in the sand of many rivers, was used.
2. A wooden pistil to fix the piece for grinding.
3. A convenient adhesive such as pitch or asphalt.
4. A rotating base of copper or iron.

The first three features remained nearly unchanged until modern times. But the last feature, the aspect of greatest relevance to the quality of the grinding piece, experienced significant evolution throughout the centuries, as we will see below.

In figures 5–8 in the next chapter we see more examples of the remarkable lens-making skills of the monks in the High Middle Ages. Two other European museums hold rock-crystal lenses made in Antiquity and the Medieval Age in the Orient. More than thirty pieces of finely ground and polished lenses from the Mycenae culture (approximately 1600 B.C.) now reside in the Harakleion Museum in Crete.

In Fornsal Museum in Visby on Gotland Island in the Baltic Sea, there are several rock-crystal lenses of different sizes and quality. The largest ones can be used as “reading stones” (see next chapter), and they all have very distinct aspherical surfaces. They originated in the Viking period (eighth to eleventh centuries), and have been discovered in different treasure troves on the island. These lenses were not made by the Vikings themselves, but were obtained through trade, exchange, or robbery in the Mediterranean Sea region.^{8,9,10}



The Reading Stones (*lapides ad legendum*)

AT SEVERAL MONASTERIES and churches in Germany and Switzerland, and in a few in France, we can still find liturgical art treasures dating back to the eighth century. France has fewer such specimens because these smaller art treasures were often destroyed during the French Revolution. Most of the sites are richly decorated with round stones such as white and brown rock crystal, amethyst, and almandine (or almandite).

A careful examination reveals that all of these stones have plano-convex surfaces, where the convex side is ground more or less distinctly aspherical (figures 5 and 6). Often the curvature of the convex surface is very strong. If we put such a stone with its plane surface on a script, then we see the writing more or less magnified (figures 7 and 8). Surely the magnifying power of crystals ground in this manner was recognized very quickly by their makers. We can therefore assume that this feature was already well known in Antiquity. The skilled monks in the High Middle Ages likewise knew this optical effect well, and during earlier centuries it was the only remedy against the *weakness of old eyes*, or what today we call *presbyopic eyes*.

But it was an imperfect solution to the ophthalmological problem. First, because such a stone needed to be placed directly on the text, it could only help for reading. For writing it was entirely useless. Secondly, it only magnified the letters, but they remained unclear on the retina. From an optical viewpoint, the reading stone was a magnifying glass and its refracting power was in the range of 30 to 40 diopters. It did nothing to correct the wrong focal length of the human eye lens.

The optical principle of a spectacle glass is, however, completely dif-

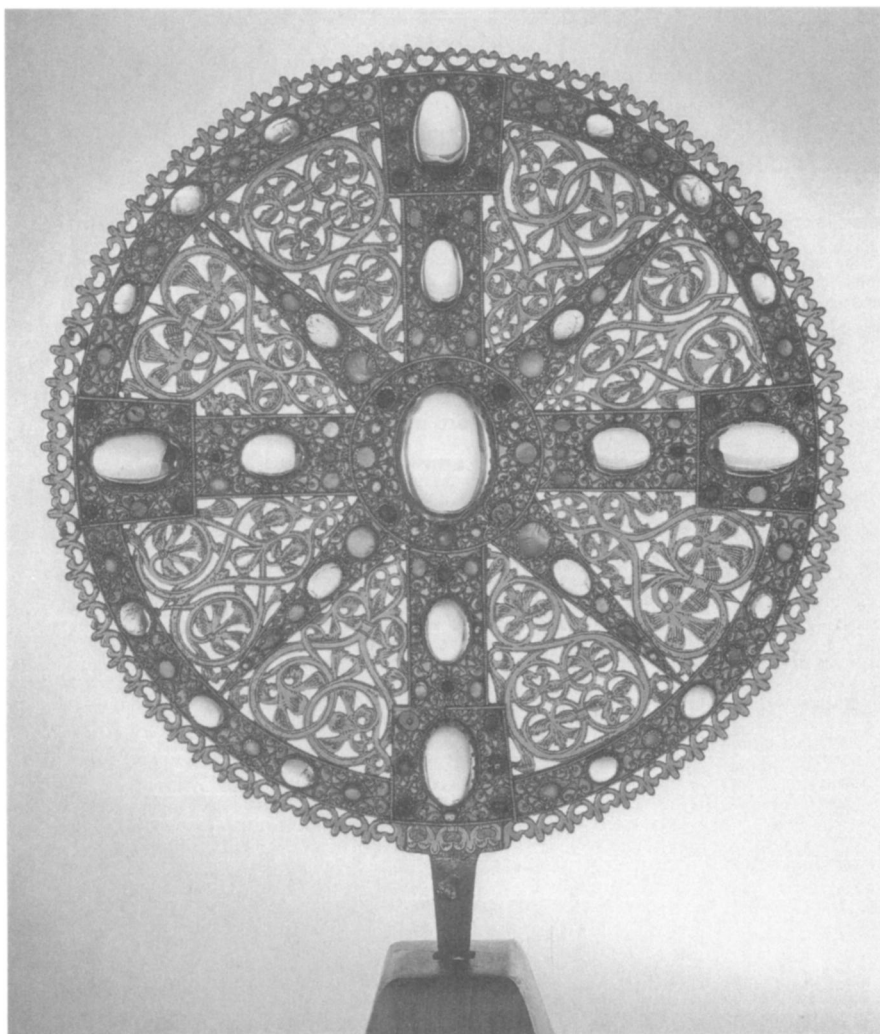


FIGURE 5. “Scheibenkreuz.” Treasure of the cathedral from Hildesheim (Germany), about 1140. The diameter is 41.5 cm.

ferent. It works as an ancillary lens with its positive refracting power to compensate the too-weak power of the lens in the human eye. The deficiency of power in the human eye lens, and therefore the positive power of a spectacle glass, is in the range of 2 to 4 diopters. To emphasize this very different optical principle, we will call lenses with a weak refracting power of only a few diopters—ones which therefore can function as spectacles—*dioptrical vision aids*.

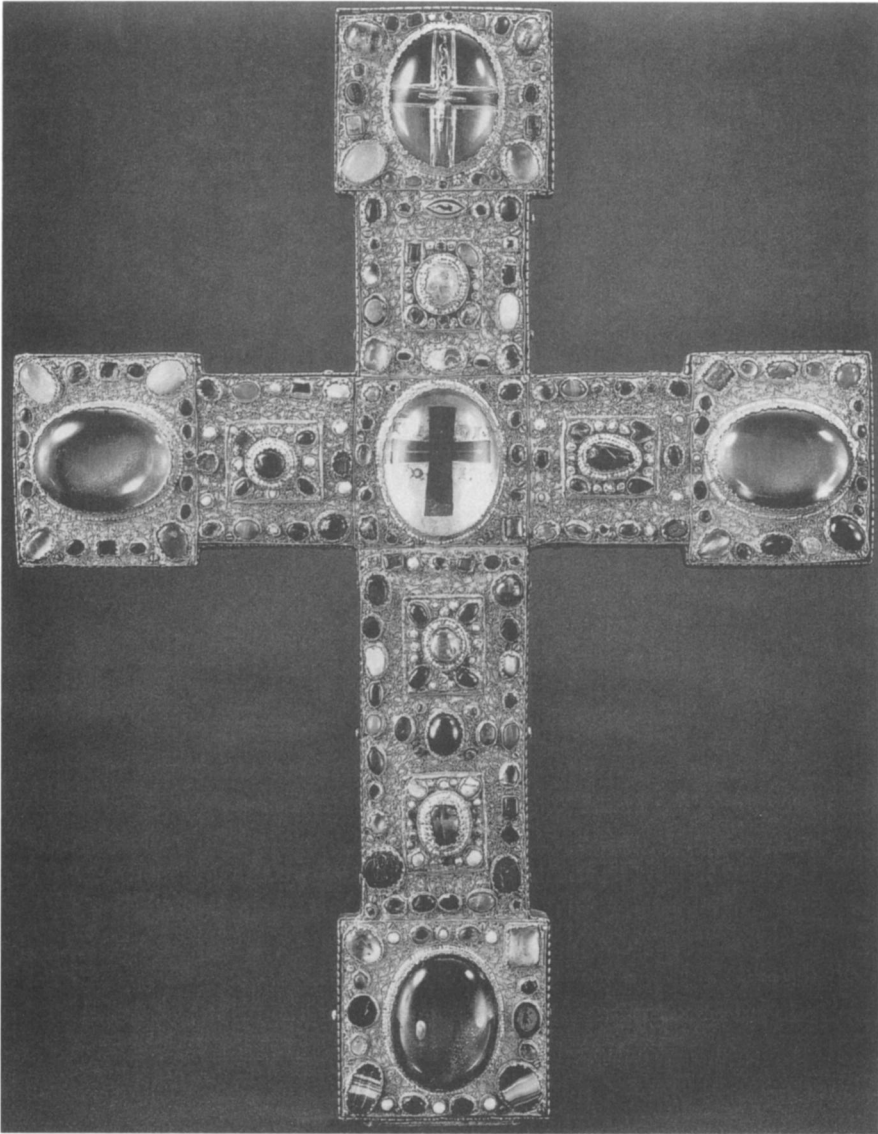


FIGURE 6. "Big cross of Bishop Bernward." Treasure from the cathedral of Hildesheim, Germany. It is the reliquary for a fragment of the holy cross, preserved behind the central stone. The German Emperor Otto III presented it to Bishop Bernward in the year 1150. It is 48 cm high and 37 cm wide.



FIGURE 7. (above)
"Reading stone" in
the plinth of the
reliquary of Holy
Stephanus. Treasure
room in the cathedral
of Halberstadt (Ger-
many), fourteenth
century.



FIGURE 8. (left)
"Reading stone"
(diameter 50 mm)
in the arm reliquary of
Holy Jacob. Treasure
room in the cathedral
of Halberstadt
(Germany).

The large range in power between 10 and 40 diopters of reading stones is of very limited help to presbyopic eyes. And because antique and medieval theories of the human eye are in this respect wholly erroneous, there existed no theoretical means of understanding that much weaker lenses would be the correct solution. Therefore there was no need to grind stones with diameters of several centimeters and with curvatures in the range of 20 cm to 1 m. Such stones would have been useless for decorative arts, and the assistance they would have provided to aged eyes remained unknown. In summary, we must recognize that as far as the invention of spectacles is concerned, the reading stone was a complete dead end.



The First Dioptrical Vision Aids

Hypothesis

Crystal lenses in diameters of a few centimeters and with refracting powers of only 1 to 4 diopters were well known, and were used as dioptrical vision aids in different monasteries long before the appearance of the first spectacle glasses in the late thirteenth century. Originally, such lenses were made for a purpose entirely remote from that of improving the vision of aging monks. The sensational development—that crystal lenses with only weak curved surfaces were also very useful for the vision of their old friars—was discovered wholly by chance. Most probably this important development was made during the critical examination of the grinding and polishing procedures.

In the following sections, the correctness of this hypothesis should be proved with different examples. But for some context, we first need a short excursion into the history of the High Middle Ages.

In figures 5–8 in the preceding chapter and in figures 9–10, we see different liturgical art objects richly decorated with strongly convex, oval or round, ground rock-crystals. The most important type is the reliquary.

Faith in the miraculous effects of the body parts, clothes, or utensils of the apostles or of other holy persons is a cult that came in the train of the Christianizing of the Germanic people from the Orient in our regions. The natural religions didn't understand the admiration of relics.

Originally such relics were very small fragments of bones, splinters from the holy cross, a pinch of blood-soaked soil from the hill of Golgatha, a tiny shred from the garment of an apostle, or a dozen hairs from



FIGURE 9. Reliquary in the shape of a pilgrim's bag. Present of the Emperor Charles the Great to "Widukind," Duke of Saxony, in the year 785. It is 16 cm high and 7.3 cm wide. Museum for Arts and Crafts, Berlin.

a martyr. If a town or a rich monastery was able to acquire such an important relic, the new location would become more frequented by pilgrims, whose presence naturally brought significant income to the region. The relics were often locked up in a reliquary. The latter could be a small case or a cross fashioned such that the relic was hidden behind the central crystal. Therefore the relics were not visible, but their presence was sufficient for the faithful (figure 9).

Toward the end of the eleventh century, political events of the highest influence in the Latin West took place. In the year 1095, Pope Urban II

issued an appeal for the first crusade, and from all pulpits of the Christian world, knights and all such aspirants, were challenged to crusade for the liberation of Jerusalem and the Holy Sepulchre. The 200 years that followed this appeal were completely subordinated to this goal.

One of the many consequences of the crusades was a flood of relics: in the Holy Land, the bones of the apostles and the splinters of the Holy Cross were collected by the hundredweight. Those knights and campaigners who returned from the Crusades often enriched themselves with the relics they brought home. From the reconstruction of the skull fragments of Saint John the Baptist, we can assume that this man must have had at least six heads.

On July 23 of the year 1164, Reinald von Dassel, Imperial Chancellor and Archbishop of Cologne, accompanied by the peal of bells and the jubilation of the people, entered the town with the bones of the three Magi. His successor commissioned a large gilded reliquary shrine as a receptacle, and this object is still venerated today in the cathedral of Cologne. The city became, for centuries, an important place of pilgrimage. Very few locations had sufficient funds to acquire such important relics and to make such an enormous and splendid reliquary.

But a fundamental change in the style of the reliquaries was the consequence, and we will now see how this innovation was of the highest importance in the solution of our problem. The custom of hiding the relics within a case or cross underwent significant change in the subsequent period. Every town or monastery that acquired one or even several of the relics was proud to exhibit these precious items to all the faithful for their admiration. Therefore the miraculous relics, typically several centimeters in size, began to be presented behind the protection of transparent rock-crystal plates.

Often, such reliquaries protected relics of different saints and martyrs. One such reliquary is, in its original condition, in the possession of the cathedral of the town of Halberstadt in Germany (figures 10 and 11). The different relics kept in it were acquired by Bishop Bernhard von Krosigk in Constantinople during the fourth crusade, and after his return in 1208 were presented to the cathedral. The reliquary itself was made between 1220 and 1225, and is called a *plate-reliquary*. The dimensions of the wooden plate are 405 mm × 450 mm, and the surface is completely covered with gold filigree. Twelve round windows are cut into it, covered by

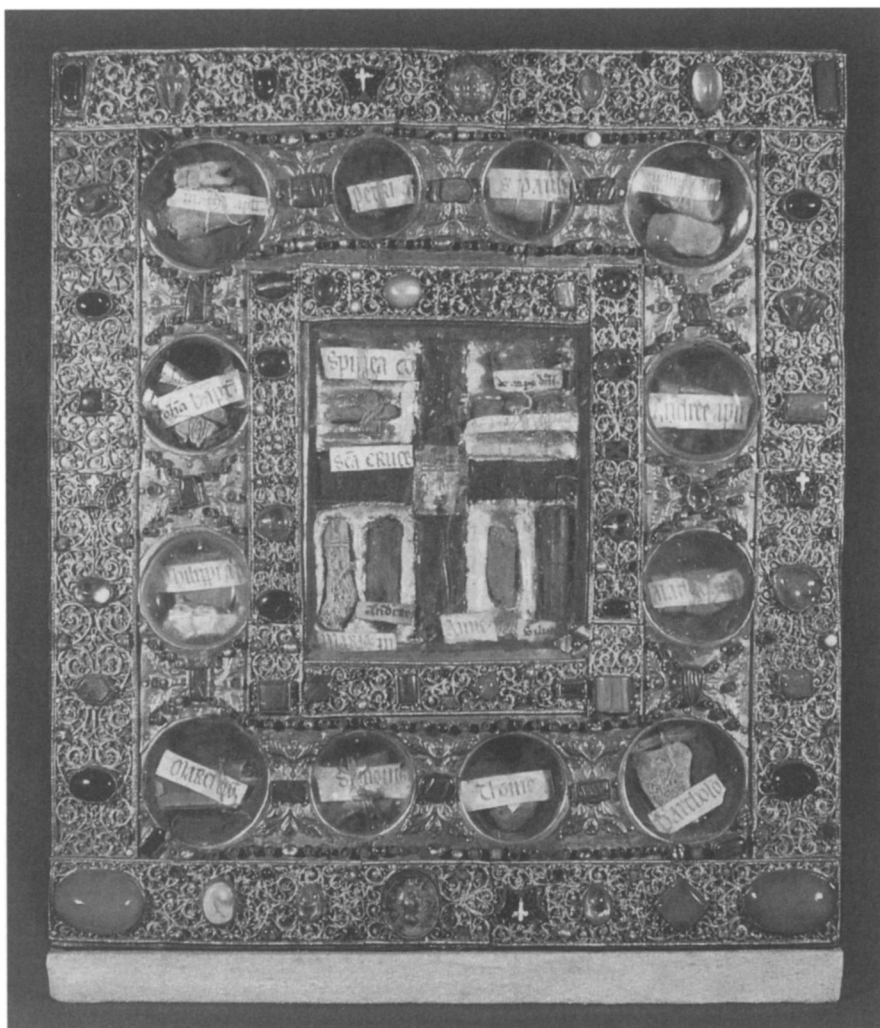


FIGURE 10. Table reliquary, made between the years 1220–1225. Treasure room in the cathedral of Halberstadt. Measurements 405 mm × 450 mm.

rock-crystal plates preserving and displaying twenty-one different relics behind them. For example, there are relics from the twelve apostles, from the Virgin Mary, and from John the Baptist. In the central part we see a large rectangular window made of a large rock-crystal plate of 140 mm × 158 mm. This contains a splinter of the Holy Cross and a thorn from the crown of thorns. Because each of these relics has a specific curative power, the faithful often attributed to them the power to heal all illnesses, from leprosy to gout to lovesickness. This kind of reliquary was much cheaper than the vast golden shrines in which complete bodies could be preserved.



FIGURE 11. Rock-crystal plate no. 4 (counting clockwise from top left), diameter 64 mm, from the table reliquary (figure 10).

We can therefore assume that this was the typical style of reliquaries during the two centuries of the crusades.

While the relics themselves are not of interest to us, the rock-crystal windows are—especially their optical properties. It is easy to see that the crystals used are of nearly perfect clear transparency, and many of the plates have a convex surface of moderate curvature. Their surfaces have been measured by the author with the coordinate measuring device already described. The curvatures of the posterior faces, which are not accessible, have been approximately measured by the Foucault test with the help of ring diaphragms of different diameters and a bright light point. The thicknesses of the crystal plates are not of great importance to their optical properties, but they could be estimated with the same bright light ray.

If we make the logical assumption that all plates have been cut at right angles to the crystal axis, we know their refracting index is $n = 1,553$, and we can therefore calculate the refracting power of the different plates from the curvature measurements. Some results are depicted in figures 12–16 where the lines, indicated with numbers, are zones of constant refracting

(Text continues on page 22)

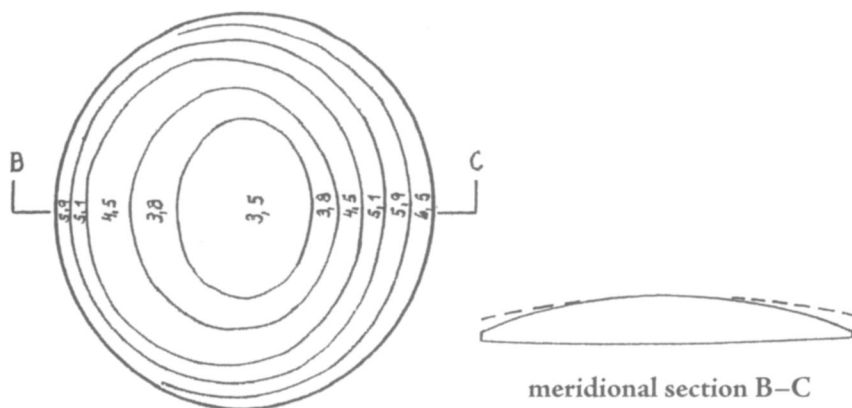


FIGURE 12. Plate no. 1 (diameter 64 mm).

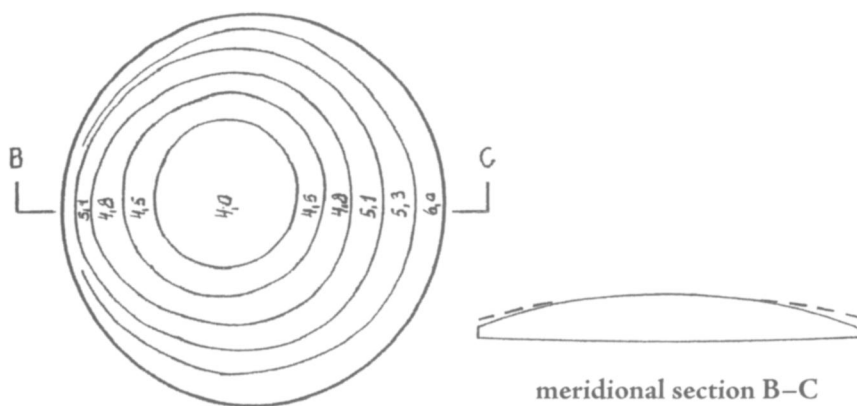


FIGURE 13. Plate no. 4 (diameter 64 mm).

Lens-plates of the table reliquary of Halberstadt cathedral

In the following diagrams (figures 12–16) we look at five of the twelve circular rock-crystal plates of the table reliquary (figure 10). Illustrated are the four plates that have the best lens quality (figures 12, 13, 15, and 16) and one plate (figure 14) that is an example of a plate unsuitable as an optical lens.

Plate numbering indicates position on the reliquary, reading clockwise from top left.

The irregular curves are the lines of equal refracting power, indicated in diopters. In the meridional section, the dotted line indicates the ideal sphere; the solid line depicts the measured curve.

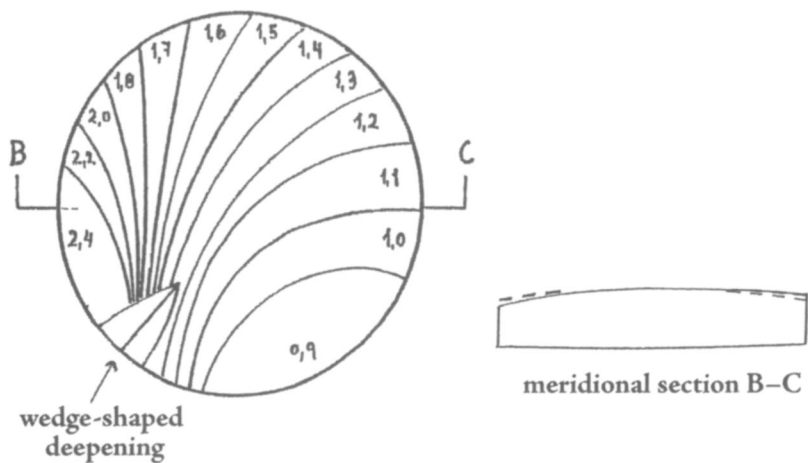


FIGURE 14. Plate no. 5 (diameter 56 mm), unsuitable as an optical lens.

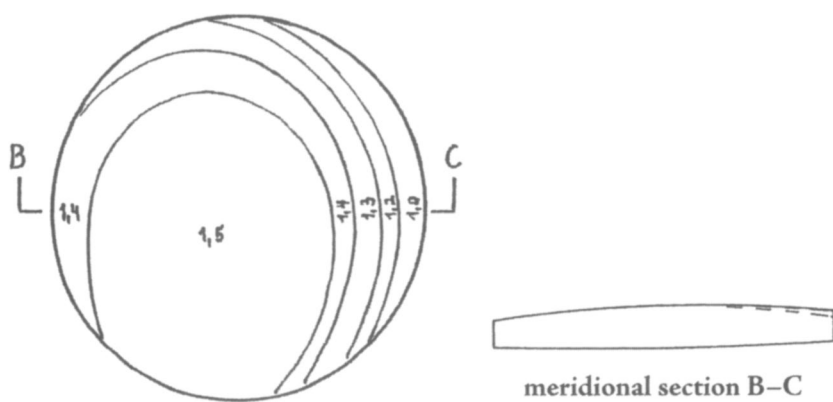


FIGURE 15. Plate no. 7 (diameter 59 mm).

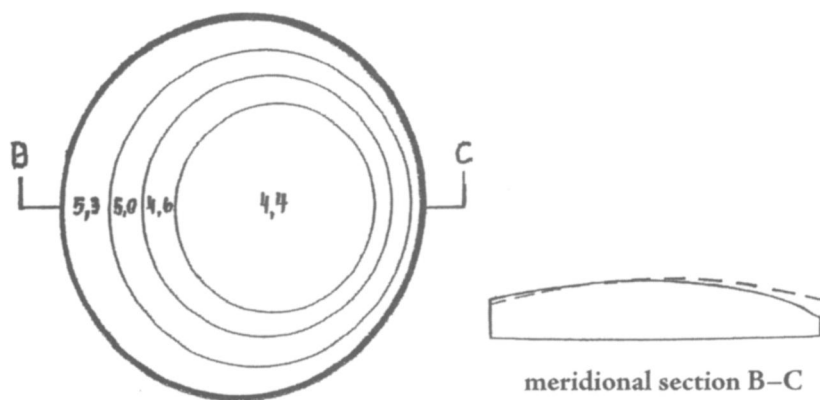


FIGURE 16. Plate no. 12 (diameter 56 mm).

power measured in diopters. The diameters are 5.5 to 6.5 cm. The plate at the top left in figure 10 is no. 1 (figure 12). As we count clockwise, we see that three of the large edge plates and plate no. 12 are of a surprisingly high-optical quality. But we also recognize that all of these plates have clearly aspherical surfaces with the curvatures becoming greater toward the rim. This makes it clear that these high-quality rock-crystal lenses were ground in the same way that was already in use in Antiquity, namely by a rotating plane surface.

In order to demonstrate the actual optical performance of these rock-crystal lenses, I made a replica of plate no. 4, but from glass instead of rock-crystal. For this purpose a grinding and polishing machine proposed by J. G. Leutmann (*Neue Anmerkungen vom Glasschleiffen*) (Halle, 1738) was copied (figure 17, A and B). The simplicity of such a machine lets us assume that it does not differ seriously from the machines used by the monks to grind crystal lenses in the twelfth century. The result was a glass lens with nearly the identical aspherical distribution of the refracting power as at lens no. 4. In figure 18 we see a medieval text as a presbyopic eye of + 4.2 diopters would see it from a distance of 25 cm. If we now put the replica in front of the eye, the text appears again very clearly with a fairly large field of view (figure 19). Outside the clear field, the script becomes increasingly blurry, according to the growing asphericity of the lens toward its rim.

Lenses no. 1, no. 7, and no. 12 show similar results according to the different refracting power of their central regions. Most of the other lenses are also of good quality, but had refracting powers of less than 1 diopter, and were therefore useless for presbyopics. And there are also several with very irregular surfaces, as we can see from no. 5 (figure 14). It seems that some of the lenses were made by skilled masters, while others were obviously fashioned by inexperienced apprentices. The big rectangular central plate has an irregular optical surface.

The development of the high optical quality of these rock-crystal plates is fairly surprising, and it indicates that the grinding and polishing technology had reached an elevated level in the monasteries and the stone-grinding workshops of the twelfth century. For this reason we can also infer that at the same locations where the stone-grinding technique was of high quality, the crystal plates with the best lens shape could be used as dioptrical vision aids. These aids were surely necessary because there

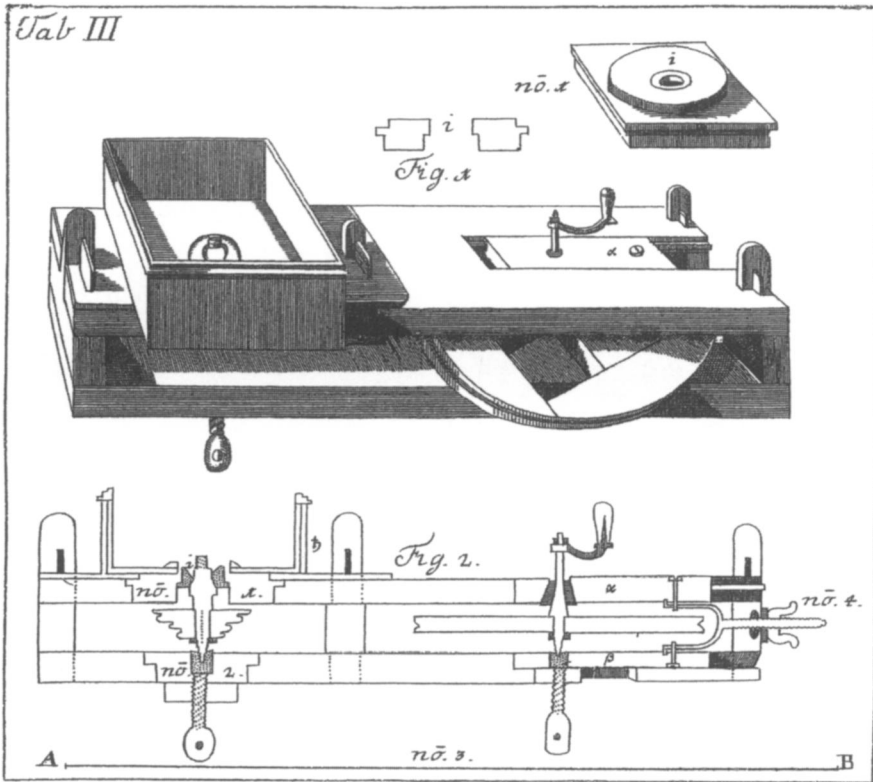


FIGURE 17A. Grinding and polishing machine of the early eighteenth century. From Johann Georg Leutmann *Neue Anmerckungen vom Glasschleifen*, Halle, 1738.

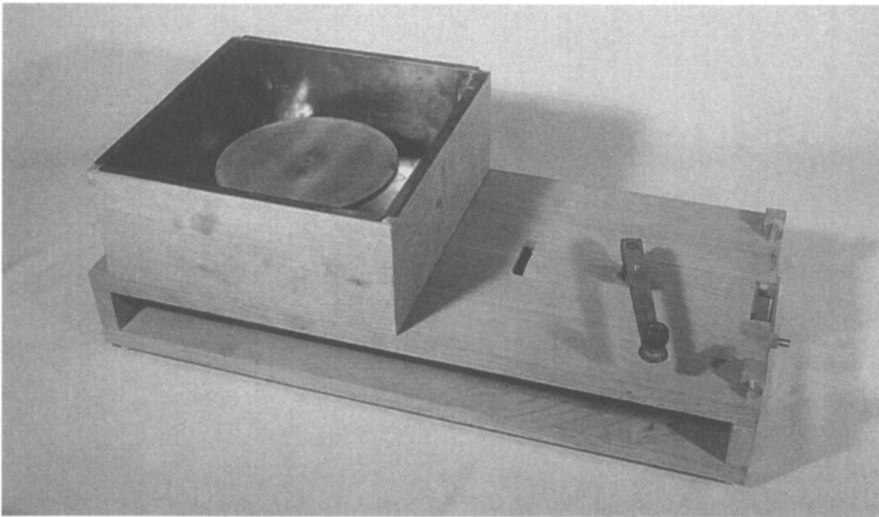


FIGURE 17B. Modern replica of Leutmann's grinding machine.

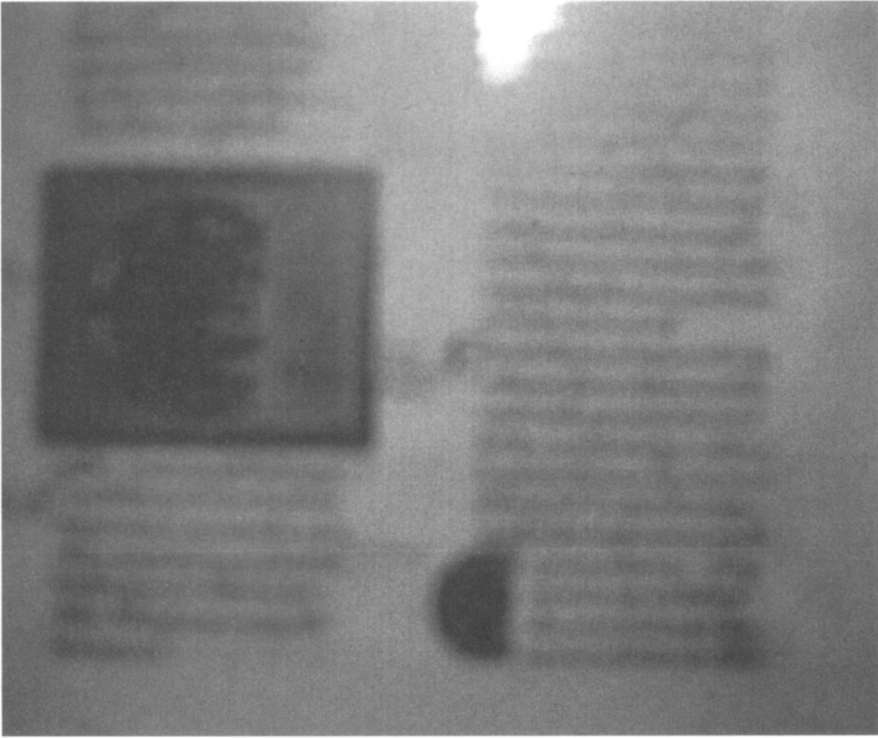


FIGURE 18. A script at the distance of 25 cm (as viewed by a presbyopic eye of + 4.2 diopters).

were many older monks in the scriptoria of the monasteries who suffered from presbyopia. There is no question that the monks soon realized that the best of such crystal plates offered dramatic improvement in the vision of their older confreres, especially if these objects were placed directly in front of the eyes.

Assigning an exact date is clearly impossible. But we can assume that the development of the optical effect of special curvatures of such crystals was made in various monasteries rather soon after the flood of relics from the first crusade, in the first half of the twelfth century. After that date the requirement of such crystal plates for reliquaries steadily increased, and the skilled grinding of such rock-crystal lenses became routine. The best of these lenses were separated and mounted in wooden frames for use as vision aids for the older monks.

We find what may be the oldest depiction of such a dioptrical vision

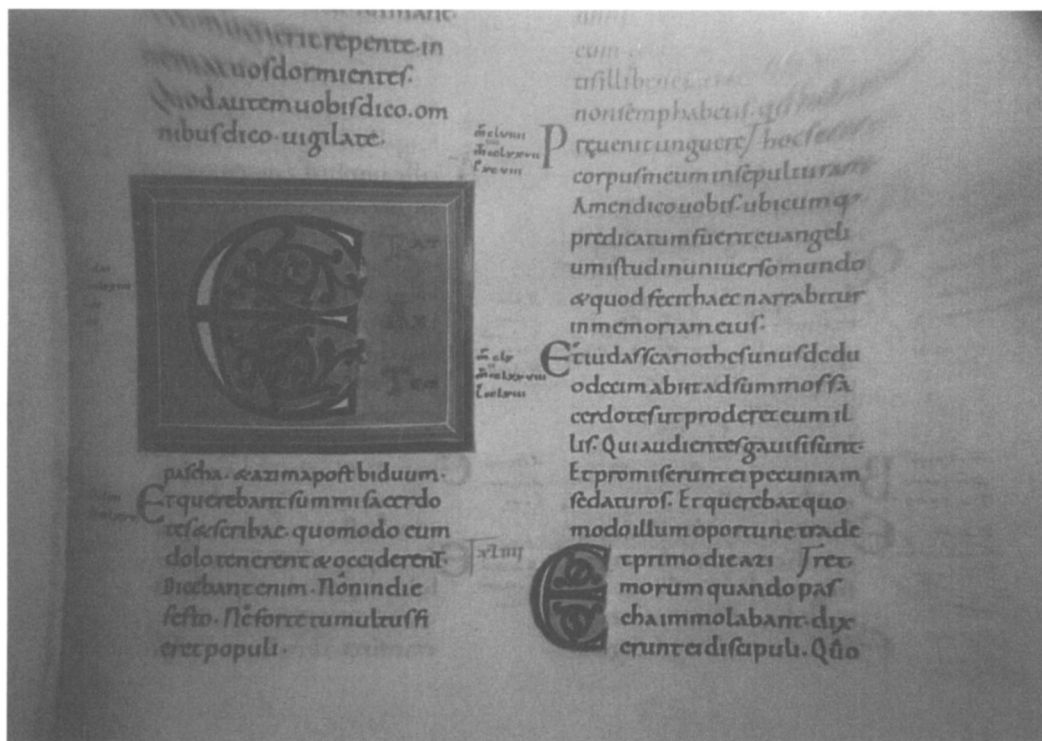


FIGURE 19. The same script as it would look if the reader had the replica lens no. 4 (strongly aspherical) directly in front of his eye and looked through the central part.

aid on a sculpture in the cathedral of Constance (Germany). It is part of a cycle of figures in the so-called *Holy Sepulchre* in the rotunda of Saint Mauritius. This rotunda and the figures were built in the years 1250–1260, more than twenty years before the appearance of the first spectacles in Northern Italy.¹¹ The figure carrying this dioptrical vision aid in his left hand is Hippocrates the famous physician of Antiquity (figure 20). Because of its slight curvature, it is obvious that this monocular is a dioptrical vision aid and not a strongly convex reading stone. A reading stone, moreover, would never have been mounted in a frame, because it must be placed directly on the script. It is also important to recognize that this vision aid was attributed to Hippocrates. It indicates during that early time such an object was a sign of age and wisdom. Therefore it could not have been completely novel in the second half of the thirteenth century.

We find another significant image (figure 21) in a fresco in the chapter

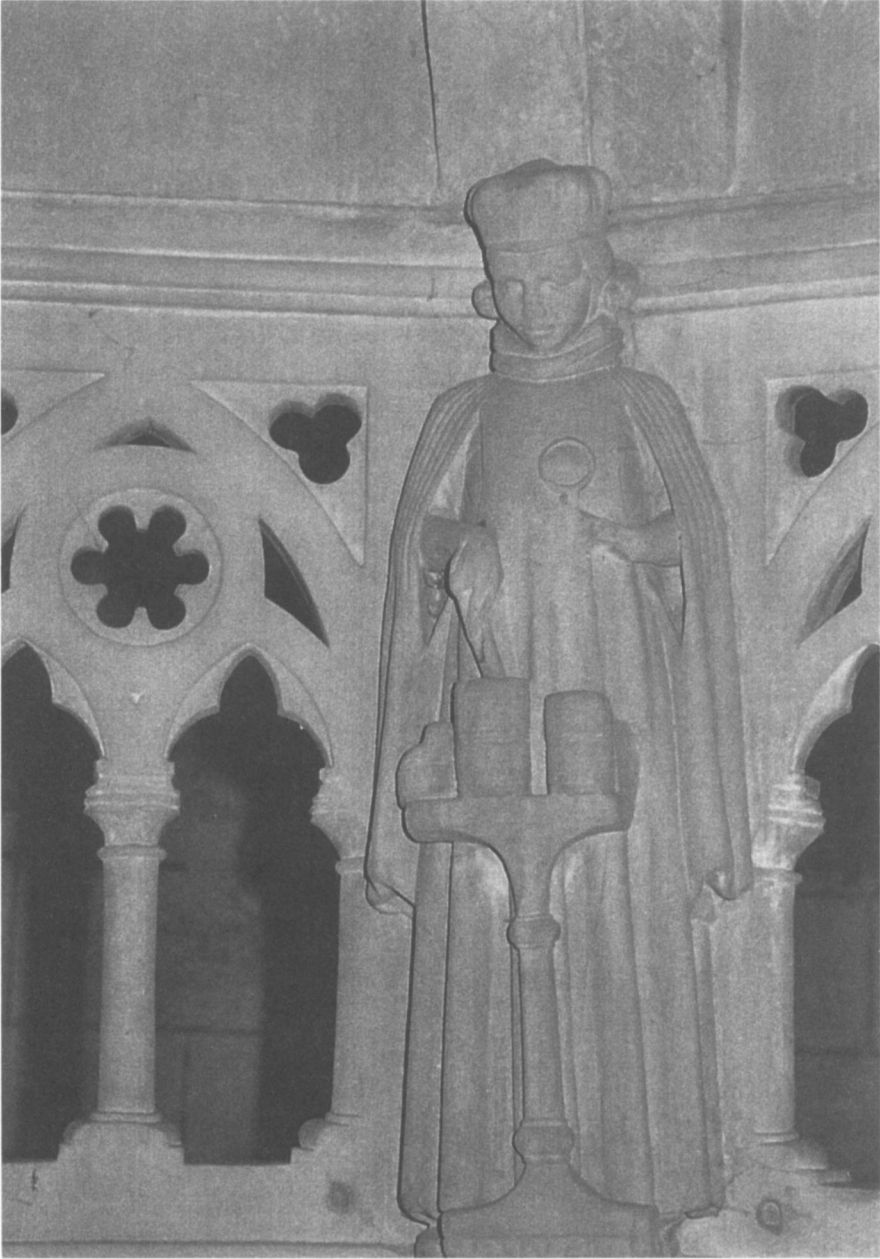


FIGURE 20. The Greek Hippocrates as a pharmacist, holding a dioptric vision aid as a symbol of age and wisdom, in the so-called “Heiligen Grab.” Mauritius-Rotunda of the cathedral of Constance (Konstanz, Germany), about 1260.

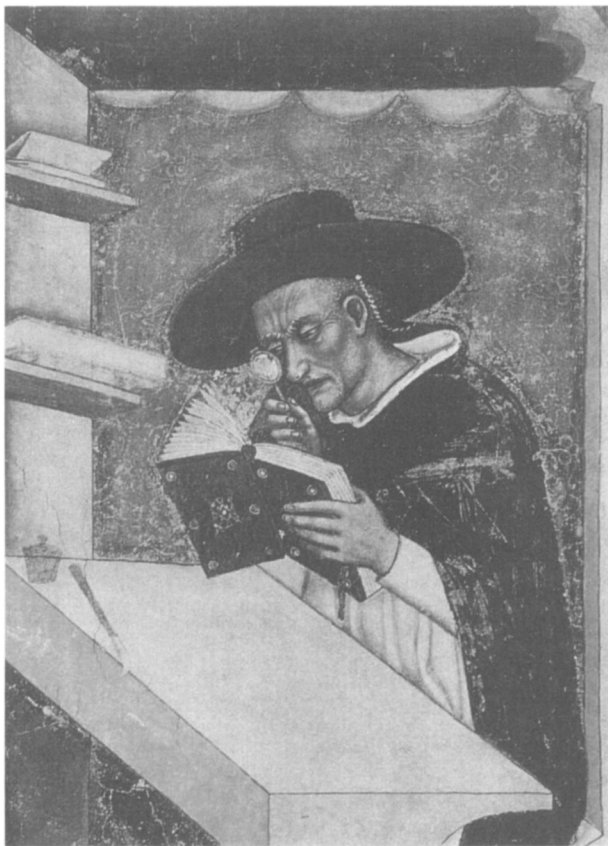


FIGURE 21.
Cardinal Nikolaus
of Rouen with a
dioptrical vision aid.
Portion of a fresco by
Tomaso da Modena in
the chapter hall of the
Dominican monastery
of San Nicolò, in
Treviso (northern
Italy), 1352.

hall of the Dominican monastery San Nicolo in Treviso (North Italy). It depicts Cardinal Nicholas of Rouen, who holds a dioptrical vision aid directly in front of his right eye while reading a book. It was painted by Tomaso da Modena in the year 1352. This picture also clearly shows that it is not a magnifying glass, because of the simple optical reason that the distance to the eye should be long and the distance to the book short. In this image, however, the exact opposite is the case. The painting is also of great interest because it makes clear that after the invention of spectacles in the late thirteenth century, rock-crystal vision aids did not go out of use for some time. Cardinal Nicholas' vision aid is a rock-crystal and not a glass lens. From the picture, we see that it had a diameter of approximately 5 cm. That is exactly in the range of the crystal lenses we have already examined and whose central thickness we have calculated as about 5 mm. But

as we will explain in detail in chapter 5, in the thirteenth century it was impossible to make lenses with such a thickness from glass.

With this knowledge we see that the defined hypothesis is correct. The monks clearly recognized that the remedies for the weakness of aged eyes were not medicines and tinctures, but instead carefully ground and polished crystal lenses. In principle, this insight would signal the departure of optics from the impractical domain of philosophical science. But even with the monks' new knowledge of crystal lenses, the route to the invention of glass spectacles had several obstacles to overcome:

1. The grinding of these crystal lenses was enormously time-consuming and required a great deal of skill and experience.
2. Even the best glass of that epoch, also called *white glass* from Venice, was distinctly colored, normally with a green tinge. A greater problem was that it was so full of air bubbles that it was completely useless for every optical application.
3. In the thirteenth century there was not any grinding technology that would have made it possible to grind lens surfaces with a desired curvature. The refracting powers of the crystal lenses varied, as a result of chance, over a broad range. As we saw earlier, the lenses were ground with rotating plates, exactly the same technique that had been in use since Antiquity. Therefore it was also completely impossible to grind pairs of nearly identical lenses as was needed for spectacles.



Glass Techniques in the Middle Ages and the Invention of Spectacles

The *Schedula* of Theophilus

We are fairly well informed about the construction techniques of a glass oven, glass melting, and glassblowing, as they were used in the High and Late Middle Ages. The very detailed source of our knowledge is a manuscript called the *Schedula*, first edited by G. E. Lessing in the ducal library at Wolfenbüttel (Germany) and published in the years 1774 until 1781. For a long time the author and the dating of this important manuscript were subjects of controversy. Today it is securely attributed to the famous goldsmith Roger of Helmarshausen, who worked in the early twelfth century. He was the maker of different liturgical works of art, especially the large altar in Paderborn (Germany). Born in the diocese of Lüttich about 1070, he worked for a long time as a goldsmith in the Panthaleon monastery in Cologne, where he took the name Theophilus and began composing the *Schedula*. After the transportation of the relics of Saint Modoald from Trier to the monastery Helmarshausen, he also moved to that location to make the necessary reliquary for these relics and other liturgical artworks. At Helmarshausen he finished the *Schedula*, in approximately 1225, a few years before his death.

We consider the *Schedula* an instruction handbook for the glassblowers' trade. In it we find detailed descriptions for the construction of the melting, cooling, and stretching ovens. We also find prescriptions for the different components of the glass and their mixture. It includes an especially detailed prescription for making potash from the ash of beech wood. The melting process and its control are also described, and at the

end, the author portrays all of the different techniques for glassblowing, especially making plate glass by blowing into a cylinder.

Glassblowing and glass grinding in Venice in the thirteenth century

Even today it remains unproven whether the roots of the Venetian art of glass melting and blowing go back to Roman times. The oldest relics of a glass oven were found in 1961 and 1962 on the lagoon isle of Torcello.¹² These objects could be dated to the seventh century, and further finds seem to confirm glass production in the eighth and ninth centuries.

It is an important circumstance that at the order of the doge Dandolo, during the fourth crusade in 1203 and 1204, the Venetians conquered Constantinople and founded the so-called *Latin Empire*. This opened up unrivaled access to the important market in the East. Glassmaking and glassblowing in Venice thereafter became a large industry capable of further development.

Glass was made largely for items that were used daily such as bottles, drinking vessels, and lamps, and it was also manufactured, in richly colored form, for cathedral windows. The manufacturing of uncolored glass was especially difficult and was highly valued. The transparency of clear glass was spoiled, however, by the presence of numerous bubbles, though these were nearly invisible in colored glass.

Glass is made from the following four components:

1. The vitreous substance itself,
2. The melting-point reducer,
3. The stabilizer, and
4. Additives.

The main component is the glassy substance itself. It is quartz sand (SiO_2), but its melting temperature of 1700° Celsius is much higher than medieval ovens could muster. It was discovered very early, however, that certain substances such as potash (K_2CO_3) or soda (Na_2CO_3) had the ability to lower the melting temperature considerably. Because such a mixture alone is completely unstable—it dissolves in water—lime or feldspar was used as a stabilizer. Additives were also used to modify the

property of the melt in the desired way; oxides of different metals, for instance, produced glass of various colors.

The effect of melting-point reducers

In the wood-fired glass-melting ovens of the Middle Ages, it was possible, if the bellows had been activated vigorously, to get a temperature of at most 1200° Celsius. Though this was far from the temperature needed to melt the quartz sand, the addition of potash considerably reduced the melting temperature of the mixture. The degree of this reduction depended on the amount of potash mixed with the quartz sand. Unfortunately, glass with too much potash additive has very unwelcome effects. To understand this we need some knowledge about the molecular structure of quartz and potash.

The K_2CO_3 molecule is, as is usual in all ion crystals, electrically unsaturated. Therefore it has a polarized structure with a positive and a negative end. But its special feature is that the polarization is similar to that of the water (H_2O) molecule. Therefore water and potash can very easily make a connection, which is why we call potash “hygroscopic.” The humidity in the air connects readily with the K_2CO_3 so that it dissolves into a thin paste. A mixture of quartz sand and potash, upon reaching approximately 600° Celsius, would start to melt, and with increasing temperature it would become more and more liquid. Therefore the mixture has no defined melting point. After cooling, the result is a more or less transparent piece of glass. The potash molecules connect themselves with the quartz molecules in an amorphous substance. But everywhere on the surface of this glass, we now have potash molecules with open polarized ends. These open ends connect with water molecules, which are steam in the air. They reduce the connecting forces between the potash and the quartz, and the quartz molecules fall out of the amorphous glass substance. The result would be that the glass would dissolve fairly quickly in hot water like a piece of sugar.

The purpose of the stabilizer needs explanation. If we make a mixture of quartz/potash/lime, the $CaCO_3$ molecule will connect with the potash molecule. Therefore at the surfaces of the latter all places are now occupied by $CaCO_3$ and there remains no place for water molecules, and the glass becomes insoluble.

Potash or *Topfasche* was, as the English and German names indicate, produced until the late nineteenth century through burning beechwood. K_2CO_3 is an important part of our soil. All plants, but especially the trees, soak it up into their wood. When they are burnt, the ash is filtered through water, so after evaporation all the salts from the ground remain in the pot. The main part of it is the K_2CO_3 , but it is polluted with other substances, especially iron salts, of which there exist two different combinations. The bivalent iron crystals have a green color, and the trivalent iron is yellow. The iron in our soil is normally the bivalent green variety.

For many centuries the manufacturing of potash in this way was, especially in the regions north of the Alps, a well-known profession called the *Aschenbrenner*. Potash was an important substance not only in glass fabrication, but also as *mildes Alkali*, crucial to many products used in daily life. In extensively wooded areas such as the Bohemian Forest, the Bavarian Forest, and the Black Forest, the role of the *Aschenbrenner* was similar to that of the charcoal burner, the *Köhler*. Glass melting needed not only potash, but also an enormous amount of wood for heating the ovens. The shorter the distances for the transportation of this necessary commodity, the more cheaply the resulting products could be sold.

We must now consider a question considering the production of glass in Venice. How was it possible that this city—without important wood resources—became for many centuries the leading manufacturer of the highest quality glasswares?

The secret of firebrick

The secret of Venice's high-quality glassware is not found in the literature devoted to this subject. Unfortunately we must resort to speculation, but the range of the possibilities is not very large. The crucial factor in the superior quality of this glass lay in a better melting process.

If the mixture of quartz, potash, lime, and some additives for coloring began to melt about 600° , there were so many air bubbles that it was completely opaque. The oven was therefore heated by strongly working the bellows until the temperature reached approximately 1200° Celsius. For many hours, the melt was kept in a very molten state so that the majority of the bubbles dissolved. But at such a high temperature the glass melt is an extremely aggressive liquid, and parts of the firebrick oven

would dissolve into the liquid. Thus while more bubbles disappeared at this point, the glass melt itself became more polluted by the dissolved firebrick.

This effect was especially serious for the so-called *white glass*, because here the many striates and strings were so much more visible than in the colored glass. In this period, white glass was simply uncolored glass; it was not “white” in the true sense. On the contrary, it was more or less colored by pollution from different substances, mostly bivalent iron, which gave the glass a greenish tinge. Nevertheless it was the most difficult to make, and therefore it was also the most expensive.

To reduce this troublesome formation of strings it was necessary to heat the glass at a lower temperature and for a shorter time. But as a result, too many air bubbles remained in the glass, and seriously diminished its transparency. This was the vicious cycle from which the glassmakers could not completely escape until modern times.

A step in the right direction would be to find the best clay to make the firebricks for the ovens. Today we know that most clay is unsuitable for making firebricks for glass ovens. The clay that is needed is a weathered product of feldspar—that is, sodium and/or potassium and/or calcium with aluminum-silicon-oxides. We find it in different geological deposits, in primary deposits at the locations where it originated, and in secondary deposits formed over time by erosion from water. The washing-out process characteristic of the secondary deposits evidently changed the microcrystalline structure of the clay, though until recently the process of this alteration was not fully understood. But what we do know is that only secondary deposits yield a material able to survive the damage at the extremely high temperatures of a glass oven. We must therefore assume that the Venetians found their material for firebricks in such secondary deposits, and that they were able to heat them longer, and at higher temperature than their competitors, especially those north of the Alps.

A Venetian trade regulation of the year 1284 concerning crystal-glass craftsmen

In the State Archives of Venice, we find in the *Codex membranaceus* enactments of the high council concerning the crystal-glass craftsmen. These rules are found in the section *Capitoli delle Arti*. Of a total of 53

regulations, only those that have a direct connection with our problem are cited here.¹³

De Cristellariis

*Curente anno domini millesimo
CCLXXXIII indizione, mense
novembris hoc capitulare factum
Fuit et confirmatum per dominios
justitiaros veteres, videlicet Nico-
laium Cahe, Marinum Justo et
Marinum Valareso.*

III

*Item, quod nullus de arte nostra
audeat laborare vitrum blanchum
contrafactum ad cristallum ad
smeriglum nec ad colore tripuli,
tam de arte grossa de minuta.*

XIII

*Item, ordinamus quod omnes homines
laborantes de arte vitri qui utuntur in
nostram artem, similiter quod ipsi
debeant vendere laborerii de cristallo
pro cristallo et laborerium de vitro
pro vitro. Et similiter teneantur vobis
aut supstantibus nostre artis mani-
festare furta facta pro hominibus
huius artis, ut superius dictum est,
et eius accipere sacramentum possimus.*

Concerning the crystal glassworkers

The regulation of the glassworkers, confirmed in November 1284 from the High Court. On November 12 of the year 1284, this regulation was drawn up and confirmed from the old administrators of justice, Nicolaus Cahe, Marinus Justo and Marinus Valareso.

III

That nobody of the trade dare to use white glass as an imitation of crystal glass, or counterfeit emery or counterfeit tripolitanian color.

XIII

We rule, that everybody who works in our trade, is obliged to sell objects from crystal as crystal and objects from glass as glass. Further, if anyone counterfeits objects of our trade, everybody should report this to the administrators, so that it can be punished.

What is the meaning of this trade regulation? All further paragraphs until No. XXXI regulate the trade of the crystal glassworkers. It was very important for the high court to prohibit the sale of ordinary *white glass* under the new name of the high-quality *crystal glass*. It follows that crystal glass was a completely new invention, and that the high court was aware of its enormous potential for trade in Venice.

Ordinary Venetian white glass was, as already explained, potash glass. It had a noticeable green tinge and was full of bubbles. But it already had quite good transparency, which was not normally the case with glass from north of the Alps. *Cristallum*, as it is now called, had only a very faint tinge and few bubbles. If its thickness was not too considerable, it was nearly as white and clear as fine rock-crystal, and was thus called by this name. Despite the name, we should not believe that it was comparable to our modern white glass; it was of far lower quality than our window glass.

The regulation of 1284 ends at paragraph XXXI but in the following years, until 1317, it needed elaboration from time to time. The first occasion was in January 1285, then again on January 9, 1289, on May 10, 1294, in October 1299, and again on April 2 in the year 1300. And now it becomes very interesting.

XXXX

MCCC. indicione XIII, die secundo aprilis, nos Raphael Natalis et Johannes de Fontana iusticiarii veteres ordinamus quod aliquis de dicta arte cristelarie non audeat emere nec emi facere, nec vendere vel vendi facere aliquod laborerium de vitro blanco quod contrafaciat ad cristallum, silicet botoni, manici, roidi de botacelis et da ogli, tabule de anconis et de crucibus, et lapides ad legendum, sub pena librarum X. et perdat laborerium et frangatur; de qua pena tertia pars deveniat ad cameram iusticiariorum et tertia scola et tertia suprastantibus artis.

XXXX

By enactment 13 of April 2, 1300.
We, Raphael Natalis and John Fontana, administrators of justice, give the order, that nobody of the glassworkers guild should dare to buy or sell, or allow to be bought or sold, a product made of white glass which imitates crystal, neither buttons, or poles, nor **round disks for vessels or for the eyes**, plates for crosses and **reading stones**. The penalty should be ten pounds and the products should be destroyed and broken into pieces. One third of the penalty should be given to the chamber of justice, one third to the school, and one third to the chairman of the guild.

Here we read for the first time that in Venice, in about 1300, the so-called *roidi da ogli*, “disks for the eyes” have been made. Paragraph XXXX is therefore a regulation to prevent ordinary white glass from being used to make high-quality glass objects, including *roidi da ogli*. Only *cristallum* was to be used for that purpose. There can be no doubt that with this *roidi da*

ogli, half-finished products for spectacle glasses are meant. And this was the first time, because we read nothing about it in the paragraphs of the earlier years of the enactment. Therefore the invention must have been quite new, because there was still no name for it.

But soon the expressions became more precise. In paragraph XXXXIII from June 15, 1301, the *roidi da ogli* are now called “vitreos ab oculis ad legendum” or “glasses for the eyes for reading.” Now the purpose of these discs has become entirely clear. The paragraphs from 1300 and 1301 in this regulation are the oldest written documents relating to spectacles, although they were not yet called by this name. Crystal glass at this time was likewise fairly new, and we can date it to just a few years before 1284. From this we can surmise that the date of the invention of spectacles was toward the end of that decade. This also confirms the sources mentioned in chapter 1, the sermon of Giordano da Rivalto, and the chronicle of the Dominican monastery Santa Caterina in Pisa.

Now we will discuss the secret of crystal glass production. We do not have written sources from the Venetians about their top secret, but with our modern knowledge of the chemistry of glass melting, we know that there were not many possibilities regarding the significant changes in their techniques.

The making of *cristallum*, like the invention of the first dioptrical vision aids by the monks, was prompted by political events. The disastrous ending of the crusades toward the end of the thirteenth century, and the subsequent cooling of the foregoing religious fanaticism, led to renewed interest in trade, an arena in which the Venetians gained a certain ascendancy. With their maneuverable galleys they soon controlled the whole Aegean Sea as far as Egypt. In Egypt, possibly in the port town of Alexandria, they became acquainted with a new material, *natrun*. Already well known to the ancient Egyptians and the Romans, natron (the modern spelling) was an important component in glass melting. In the hinterland, not far from the town Misr al-Kahira—known today as Cairo—there are several lagoons in a dry valley that had produced natron for thousands of years, and was therefore called “Wadi en Natrun.” Natron had been recognized thousands of years before as an important component in the process of mummification.

Experiments by the Venetian glassmakers with this new material re-

sulted in some very important insights. The natron was obviously so pure that the glass had only a very faint color tinge, a hue nearly invisible in objects of slight thickness. But even more importantly, glasses with natron as a fluxing agent to reduce the melting point became at high temperatures noticeably more liquid, and therefore fewer bubbles remained after the melting process. And, best of all, natron glasses were not affected by the humidity in the air and thus did not devitrify.

Today we know that the Egyptian natrun is soda or Na_2CO_3 . Although soda is soluble in water, unlike potash, it is not hygroscopic, and the stability of sodium glasses against environmental influences is therefore much better. Normally, natron from the lagoons of Wadi en Natrun was not pure, but contained lime, CaCO_3 . But that was not a disadvantage, because lime was necessary as stabilizer.

In comparison with other *white glasses* of this time, especially with the glasses from north of the Alps, the Venetian *cristallum* was an evident breakthrough. Also in Old Egypt, in Mesopotamia, and in the Roman Empire, sodium glass alone was used because this material was so easy to obtain at that time.¹⁴ Even today, the glassmakers of ancient Rome appear enormously impressive in their artistic design and in their knowledge of glassblowing techniques. If they had had only potash glass, we would have had no knowledge of it, because all of it would have been devitrified throughout the centuries. But the melting technique used in that early time was still too incomplete to make possible the breakthrough which occurred in Venice 1,000 years later.

The last step

In 1280 or a few years later, the second of our three remaining problems (page 28) was solved. A final step still remains. How was it possible to grind in pairs, with nothing but the old technique, thin positive lenses with fairly exact surfaces and defined refracting powers? The solution to this stubborn enigma has never been recorded. It was, like the manufacturing of *cristallum*, a carefully guarded secret of the Venetian glassworkers. We do not even find the faintest hint. There is only the stipulation that the use of ordinary white glass was prohibited for the making of the *roidi da ogli* or the *vitreos ab oculis ad legendum*.

Rivet spectacles from the monasteries of Wienhausen and Isenhagen

In 1953 in the monastery of Wienhausen, near Celle (Germany), during the renovation of the nuns' choir, an important archaeological find was made (figure 22). When workmen lifted the heavy oak planks of the floor between the two rows of the choir stalls they found rivet spectacles with the original glass still intact and in nearly perfect optical condition. There exists some detailed literature about it.¹⁵

We already knew the features of the oldest spectacles from paintings of the fourteenth and fifteenth centuries (figures 23–26).^{16,17} With this find, all three types of rivet spectacles had been found in original condition with working glasses. This was a stroke of luck for the history of optics, and will probably never happen again.

In figure 27 (page 44) we see type 1, in figure 31 (page 46) type 2, and in figure 35 (page 48) type 3. Some years later a second piece of the type 1 was found in the nuns' choir of the monastery Isenhagen near Hankensbüttel (only one-half of a spectacle; figure 37, page 49). These original spectacle glasses, which can be dated by reasons of archaeological circumstances to the early fourteenth century, are the key to the invention of the spectacles of the late thirteenth century. The author was able to examine them in detail with optical test methods.

Examination of the glasses with the Ronchi test

This test consists of a grid of fine parallel strings inserted inside the focal point (or outside of it, with an inverted test image) of the optics to be tested. Directly behind it we recognize the image of the grid. There are bright and dark lines, and in the case of a perfect lens, the lines areas are parallel, as in the test grid inside the focus. But every irregularity in the lens produces deviations of the straight lines in the test image.

Therefore in the Ronchi test, the amount and the kind of these deviations offer quantitative and qualitative information about the condition of the object under scrutiny. To test lenses we therefore need monochromatic light.

In figure 28A (page 45) and figure 89 (chapter 10, page 96) we see the Ronchi test of a perfect lens (achromatic objective). Without explaining

(Text continues on page 44)

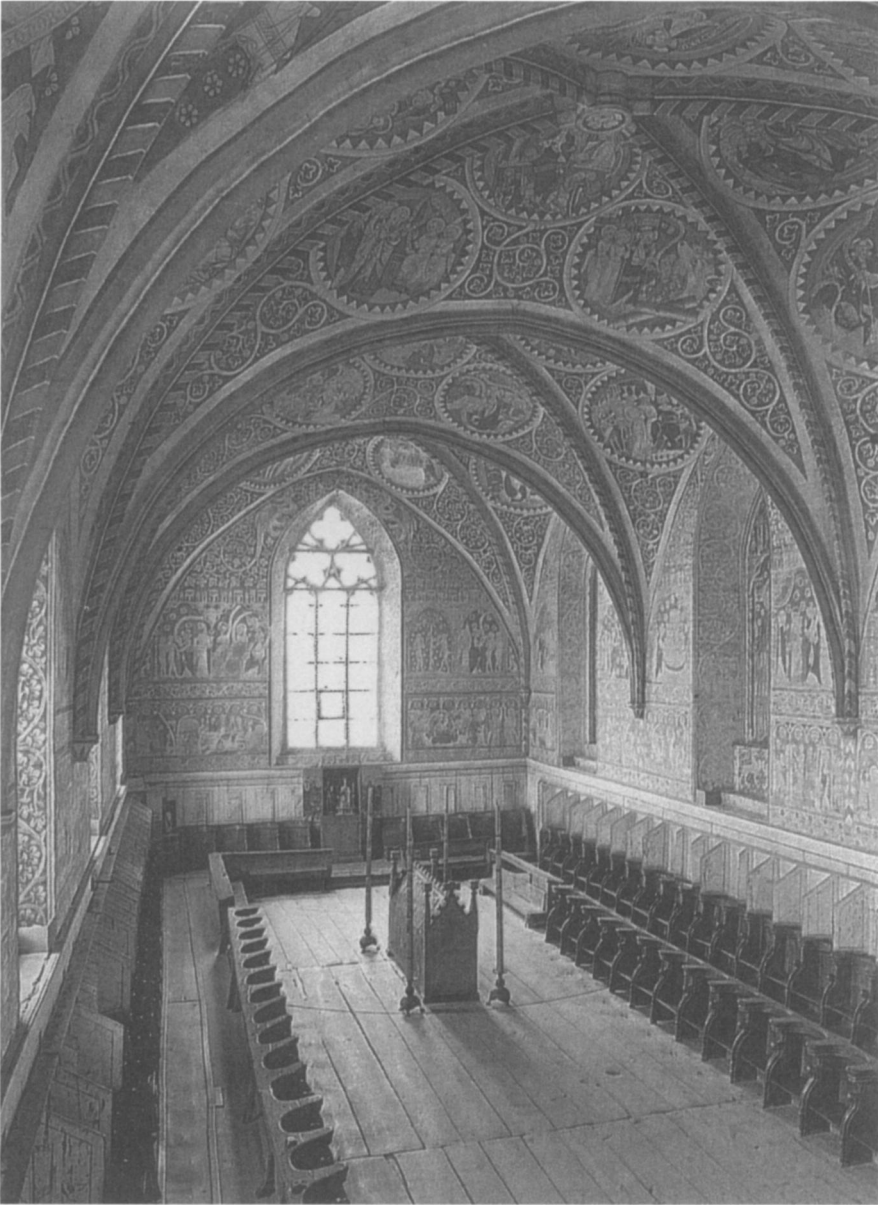


FIGURE 22. Nuns' choir in the monastery at Wienhausen (Germany) about 1350. The rivet spectacles were found in autumn 1953, together with more than a thousand other artifacts dating from approx. 1340 until 1530, in the dust under the oak floorboards between the first and second rows of seats.



FIGURE 23. Rivet spectacle, type 1, worn by Cardinal Hugo of Provence. Portion of a fresco by Tomaso da Modena (1325–1379), in the chapter hall of the Dominican monastery of San Nicolò in Treviso (Italy), 1352.



FIGURE 24. Rivet spectacle, type I. Painting by Friedrich Herlin. Part of the altarpiece of St. Jacob's Church in Rothenburg ob der Tauber (Germany), 1466.



FIGURE 25. Rivet spectacle, type 2. Painting by Jan van Eyck (1390–1441). Portion of the painting *Maria with Child*, Groeninge-museum, Bruges (Belgium).

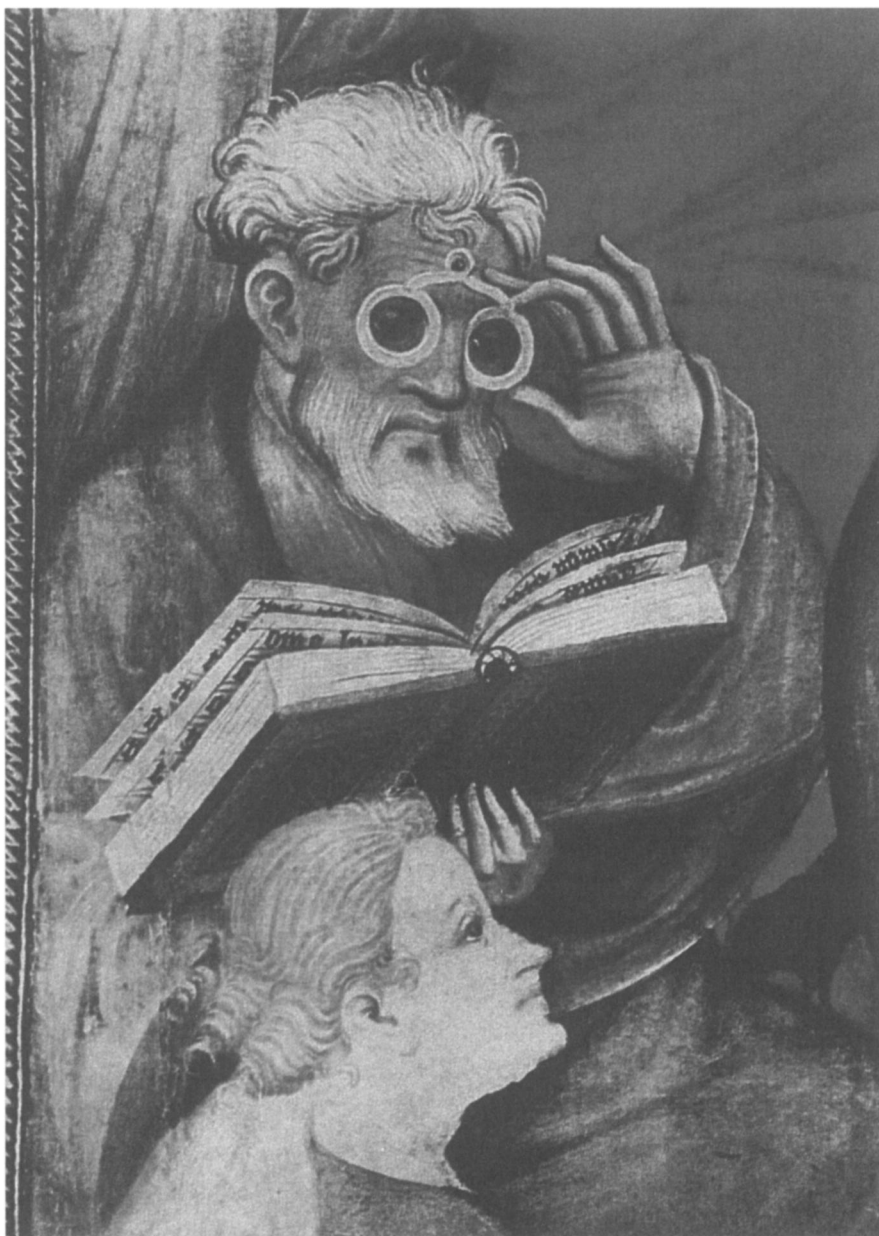


FIGURE 26. Rivet spectacle, type 3. Painting by Konrad von Soest. Part of the Pentecost altarpiece in the *Stadtkirche* of Bad Wildungen (Germany), 1403.

the optical interference relations, we can follow the simple rule that the width of a Ronchi line corresponds approximately to an aberration of one wavelength. If we see in the test image that the Ronchi lines are curved, then we can directly measure this curvature in fractions of the width of the lines corresponding to the fractions of the wavelength of the test light. It follows from the wave theory of light that if a lens has to fulfill the minimum criterion of resolution, its aberration at the focus should not exceed one-fourth of a wavelength. This is the Rayleigh criterion, which is an approximation, but is simple to use and completely sufficient for our purpose. We can therefore quickly judge, on the basis of the bending Ronchi lines, whether or not a particular lens would be suitable as a telescope objective.

Tests of the rivet spectacles from Wienhausen and Isenhagen

Figures 27 through 37 on the following pages illustrate the three types of rivet spectacles, the Ronchi tests performed on each glass with their results, and detailed views of several glasses.

RIVET SPECTACLE, TYPE I. We see in both glasses of WOI, a specimen from Wienhausen monastery (figures 27, 28B, and 29), many small dark dots and striates. There is a conspicuous astigmatism. The plane surfaces

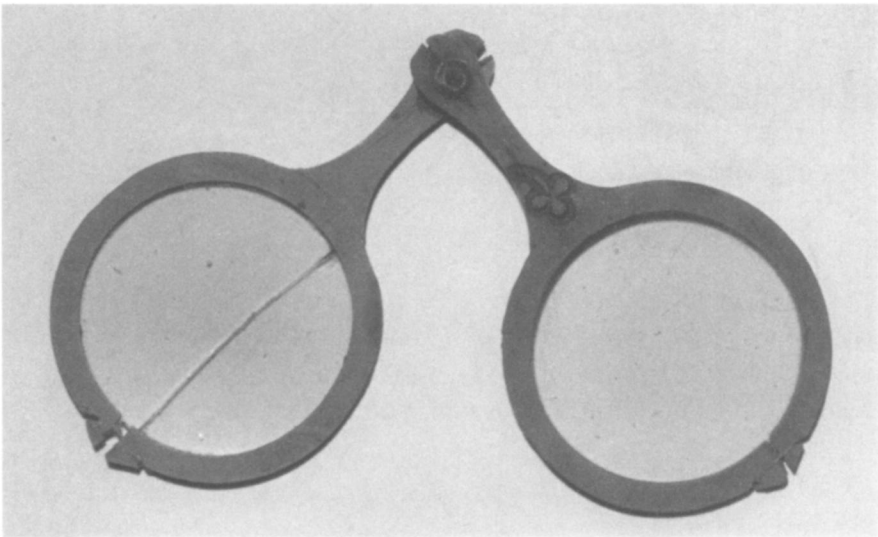


FIGURE 27. WOI, rivet spectacle, type I (Wienhausen monastery).

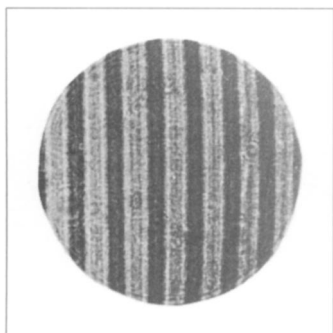


FIGURE 28A. Ronchi test.

Perfect modern lens
(achromatic objective)

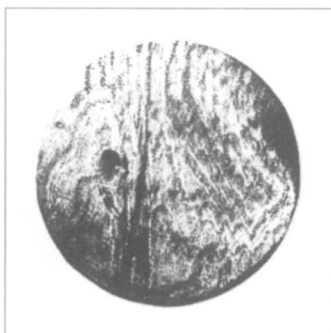


FIGURE 28B. Ronchi test.

Left glass, diameter: 30.5 mm
approximate focal length:
 $f = 287 \text{ mm} = 3.5 \text{ diopters}$

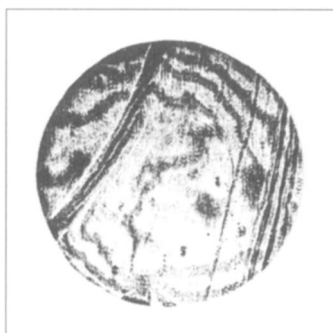


FIGURE 29. Ronchi test.

Right glass, diameter: 30 mm
approximate focal length:
 $f = 294 \text{ mm} = 3.4 \text{ diopters}$



FIGURE 30. Right glass of WOI (with cloverleaf on the frame).

are aspherical, with increasing curvature toward the rim. For the right glass, $r_2 = 1800 \text{ mm}$ in the center, $r_2 = 2800 \text{ mm}$ at the rim.

On the convex surface of WOI (figure 30), we recognize a clearly raised dot that is easy to feel with the fingertip. Otherwise with the microscope the surface looks clear, and no grinding traces are visible. On the plane surface we can see many fine unpolished and polished dots as remnants of the grinding process.

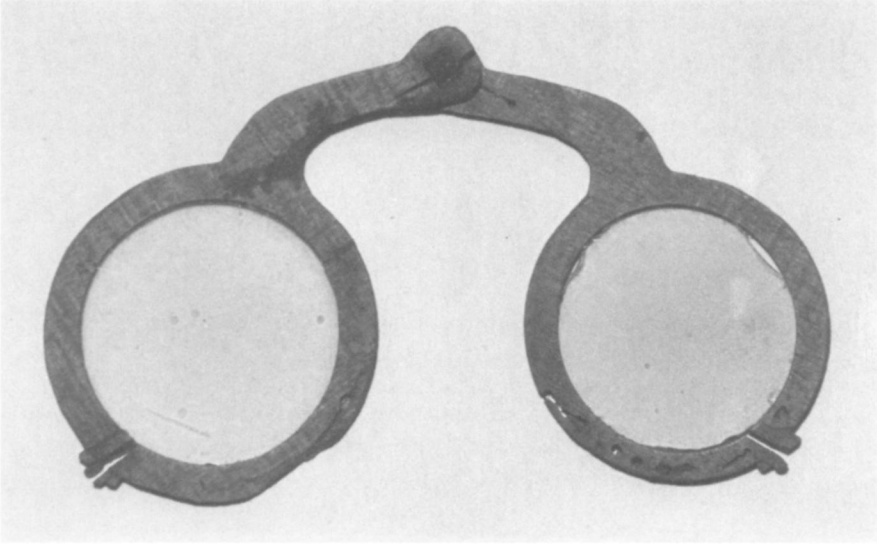


FIGURE 31. Wo2, rivet spectacle type 2 (Wienhausen monastery).



FIGURE 32. Ronchi test.

Left glass: yellow tinge,
diameter: 33.3 mm
approximate focal length:
 $f = 323 \text{ mm} = 3.1 \text{ diopters}$

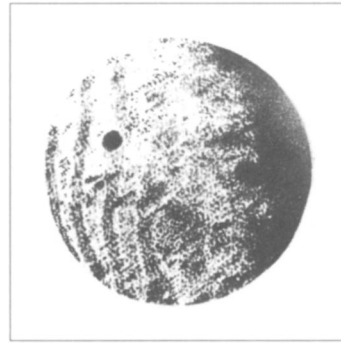


FIGURE 33. Ronchi test.

Right glass: yellow-brown,
diameter: 31.0 mm
approximate focal length:
 $f = 257 \text{ mm} = 3.9 \text{ diopters}$

RIVET SPECTACLE, TYPE 2. In specimen Wo2 from Wienhausen monastery (figures 31 through 33), there are bubbles in both glasses out to a diameter of 1 mm, and a conspicuous astigmatism. In both glasses approximate plane surfaces are aspherical with increasing curvature toward the rim.



FIGURE 34. Left glass of Wo₂ (the larger of the two).

On the convex surface of glass Wo₂ (figure 34), with the microscope toward the center, a raised dot is clearly recognizable and is also easy to feel with the fingertip. Otherwise there are no remaining traces from grinding. Plane surfaces of both glasses: especially toward the rim there are a lot of fine points as remnants of the grinding process.

RIVET SPECTACLE, TYPE 3. Both glasses of specimen Wo₃ from Wienhausen monastery (figures 35 and 36) have a faint yellow tinge, and we see various bubbles up to 1 mm diameter. There is a very strong astigmatism.

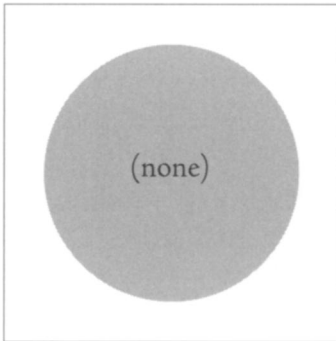
The indicated focal length is the arithmetic average of the meridional and the sagittal focal length.

On neither of the convex surfaces of these glasses is there a trace of grinding all the way out to the rim. But the approximately plane surfaces are fairly poorly polished, and include a lot of very faint dark dots and unpolished scratches as remnants of the grinding process.

PARTIAL RIVET SPECTACLE, TYPE 1. In the glass Iso₁ (diameter 28.5 mm), half of a spectacle from Isenhagen monastery (figure 37), we detect a great many bubbles of various sizes and also many striates. The quality is considerably worse than the glass of the three spectacles from Wienhausen. It has a discernable greenish tinge, and on the approximately plane surface



FIGURE 35. Wo3, rivet spectacle type 3 (Wienhausen monastery).



(Ronchi test impossible)

Left glass: faintly yellow,
diameter 31.3 mm
approximate focal length:
 $f = 279 \text{ mm} = 3.6 \text{ diopters}$
Extreme astigmatism.



FIGURE 36. Ronchi test.

Right glass, faint yellow,
diameter 31.3 mm
approximate focal length:
 $f = 287 \text{ mm} = 3.5 \text{ diopters}$
Strong astigmatism.

we see many traces of a slight devitrification and many very faint dark dots remaining from grinding. Nevertheless, the glass is fairly transparent and could be optically tested. Approximate focal length: $f = 342 \text{ mm} = 2.9 \text{ diopters}$. The indicated focal length is the arithmetic mean of the meridional and the sagittal focal length. The convex surface is fairly well preserved,

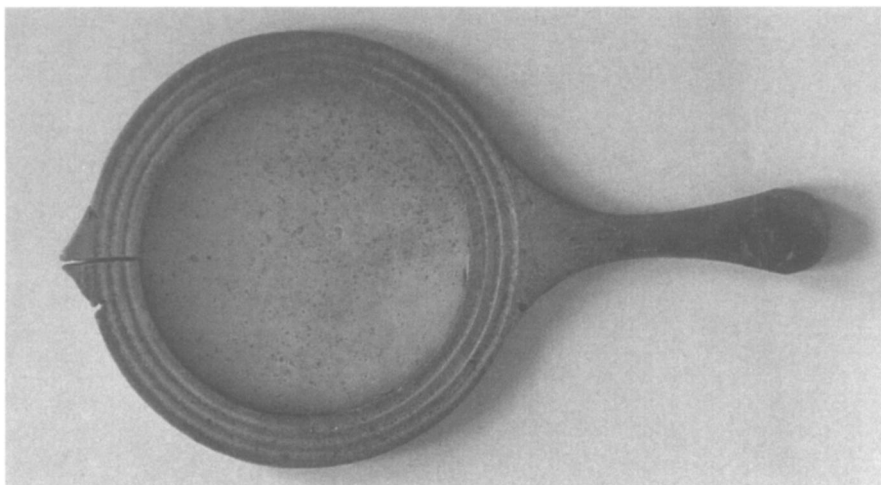


FIGURE 37. Iso1, part of a rivet spectacle type 1 (Isenhagen monastery).

with no devitrification and absolutely no traces of a grinding process. The glass exhibits extreme astigmatism; no Ronchi test is possible.

If we compare figure 28A with the Ronchi images of the glasses of these rivet spectacles, we recognize quickly from the chaotic curvature of the Ronchi lines that all these glasses are far from suitable for use as telescope objectives.

The spectacle glasses on the Gothic book-case in Lüneburg

Since 1954 a Gothic book-case (figure 38) has been in the possession of the museum of the Principality of Lüneburg (Germany). Originally this artifact was in the town hall. The case measures 23 cm × 22.5 cm and has a depth of 8.5 cm. It is decorated on the exterior and partially on the interior with richly colored paintings and carvings. On the outside of the top is a figure of Christ in the center, and at the corners, four spectacle glasses, which are painted on their posterior surfaces (that is, on the plane surfaces of the glass) with the four symbols of the Evangelists. These four glasses are spectacle glasses of the same epoch as those from Wienhausen. The book-case is datable to the year 1330.¹⁸ It was therefore of great importance to be able to examine these four spectacle glasses.

A microscopic examination quickly made clear that on their convex surfaces these glasses are completely free of all traces of grinding. We also recognized slightly raised traces on the convex surfaces, though these were



FIGURE 38. Gothic book-case from about 1330, now in the museum for the Principality of Lüneburg. At the edges of the cover there are four spectacle glasses, painted on the underside with the four symbols of the Evangelists. The lenses are made in exactly the same manner (blown glass balls) as the spectacles in Wienhausen.

not as distinctive as those of specimens W01 and W02. The glasses were characterized, moreover, by an impressive astigmatism, though they could only be examined with a spherometer and the microscope. Further optical research is impossible.

The lens on the top left is broken and could not be measured exactly. The measured radii of curvature are the following:

- L2: $r_m = 188 \text{ mm}$ $r_s \approx 132 \text{ mm}$
approximate focal length 302 mm = 3.3 diopters
- L3: $r_m = 182 \text{ mm}$ $r_s \approx 148 \text{ mm}$
approximate focal length 311 mm = 3.2 diopters
- L4: $r_m = 228 \text{ mm}$ $r_s \approx 150 \text{ mm}$
approximate focal length 357 mm = 2.8 diopters

where r_m means the meridional and r_s the sagittal curvature.

Here is a summary of the results of the measurements of the 11 spectacle glasses:

1. On each one of the plane surfaces we clearly see remaining traces of grinding. There are hundreds of fine holes, sometimes over the whole surface and sometimes only along the rim.
2. By contrast, on the convex surfaces, there is absolutely nothing visible remaining of the grinding process.
3. Some of the convex surfaces clearly show small raised structures.
4. All convex surfaces have a more or less distinct astigmatism. Their geometrical shape must therefore be described approximately by a meridional and sagittal radius of curvature. Therefore all of these lenses have two different focal points.

The difference in optical operation between a spectacle glass and a telescope objective

For a complete understanding of the following chapters, it is absolutely necessary to make clear the important differences in operation of a spectacle lens and a telescope-objective lens.¹⁹

The spectacle glass

This is not a component that makes an optical image directly. It works as an ancillary lens, which has to compensate for a lack of refracting power of the lens of the eye. Therefore it is worn directly in front of the eye, which means a distance of 10 mm to 20 mm. The aperture of the iris of the human eye in daylight is approximately 2 mm. For this reason if we look through a spectacle lens we need a section of the glass not much greater

in diameter. If an imperfect spectacle glass has a refracting power that varies about one diopter over its whole diameter, this would not seriously affect the person who wears that glass. When the viewer turns his eyes, the refracting power changes about a tenth-part of a diopter. But that is a value that also can easily be compensated for by accommodation from a strongly presbyopic eye.

The telescope objective

The telescope objective operates completely differently. It is an optical element crucial for image formation. Therefore all rays that pass through its aperture help form this image. If, for example, the central part is spherically well ground and polished, but outside this aperture from approximately 10 mm the lens becomes more and more seriously aspherical, then the greater part of the refracted rays coincide at different locations inside and outside the focal point of the central part, and the formed image becomes very unclear. And if the shape of the lens is asymmetrical, then we have different focal points in different planes. In all cases mentioned here the image of a distant object will be very blurry.

The requirements for the optical quality on a telescope objective are much more rigorous than for those of a spectacle glass. Lenses with irregular surfaces might possibly still be used as spectacle glass, but are completely useless as telescope objectives. The problem is further complicated by the fact that we require that the image formed by a telescope objective is magnified by an eyepiece glass, and that even with such magnification the image must remain clear. Therefore the telescope objective needs to be several times as accurate. For the first telescopes a magnification of three to five times was an acceptable result.

Discussion of examination results

The approximate plane surfaces of the lenses examined show exactly the same structure as the plano-convex rock-crystal lenses. They had been made for centuries in different monasteries, namely, as aspherical lenses with continuously increasing curvatures toward the rim. Therefore they had also been ground, like the crystal lenses, with rotating plane plates. Otherwise at the convex surfaces we do not see the faintest indication that they have been ground, and for different lenses we note that the convex

surfaces sometimes have raised traces containing air bubbles or black intrusions in the glass. Therefore there is no doubt that these surfaces have not been ground, because if they had been, these raised dots and striates would be impossible.

There can be only one explanation for such inconsistencies. The early spectacle glasses were segments of blown glass balls. The cutting of the round meniscus-shaped glass plates from the ball were made by using an old and well-known technique.²⁰ Immediately after the glass ball was blown, a small section of copper pipe, cooled in a bottle of water, with a diameter corresponding to the required diameter of the spectacle glass, was touched to the surface of the still-hot glass ball. The shock of cooling resulted in a break along the rim of the copper pipe. Then the pipe was cooled again, and a second, a third, and so on glass plates were cut until the whole ball surface was covered in such circle-shaped breaks. After the ball was completely cooled, it was broken by striking with a blunt piece of wood into a number of pieces and many meniscus-shaped glass discs. At this point only grinding and polishing of the concave surface to a plane was required, and the spectacle lens was complete.

Now the riddle of point 4 (page 51) is solved, namely the issue of conspicuous astigmatism. The blowing of an absolutely spherical ball with a thickness of 1.5–2 mm would have been impossible. During blowing, the ball emerges from the glassblower's pipe quickly, and assumes the shape of a pear. The great art of blowing spectacle glasses was to determine the correct proportion between the amount of glass taken out of the oven with the pipe and the required diameter, so that the ball would solidify quickly. From the measured radius it follows that the diameters of the balls ranged between 200 mm and 500 mm, which accorded the necessary refracting power of 2–5 diopters.

Now we can reconstruct the course of the invention in the following manner: In 1280, the making of the plano-convex rock-crystal plates had been around for at least 150 years in monasteries. They were necessary as protective windows for reliquaries. But it was also well known that the best of them were very useful as vision aids, particularly for older monks engaged in reading and writing. Nevertheless, the successful manufacture of such a dioptrical vision aid required both great skill and considerable luck. Grinding the hard rock-crystal to the required regularity would have been, moreover, very tedious and time-consuming.

The rumor of the invention of the *cristallum*, a very clear glass made by the Venetian glassmakers, soon came to the attention of the monks in their grinding workshop, possibly even in a monastery in Venice itself. The protagonists may have been Dominican monks, because this order is always mentioned in connection with spectacles. And these monks had the clever idea that it would be a great help to make the vision-aid plates not from rock-crystal but from this new glass, which would be as clear as the best crystals, but much less hard.

One of the monks carried such a crystal vision aid to the glassworkers in Venice and confronted them with the problem, showing them the crystal plate made in the monastery. One of the glassworkers had the following idea, which while obvious enough for a glassblower, was nevertheless ingenious: "You should not make the vision aid by grinding," he suggested. "You should, instead, blow it up as a glass ball of the required diameter. Then by cutting this ball into many small discs and grinding their concave surfaces plane, you will get a lot of equal plates, and because they all have the same shape, you could arrange them in pairs in front of the eyes, which would improve vision even more."

We can now see that the spectacle was not the result of intellectual consideration of the laws of optics. At that time, these laws, even when correct, were so few that they could hardly show the way to the invention of spectacles. The actual invention came about through numerous small steps, taken over the course of many decades, for different reasons, and never with the purpose of helping the aged eye. But one day all of the necessary knowledge was available, and required only a clever mind for assembly.

This ingenious idea of blowing glass balls in order to make identical lenses that could be worn in pairs in front of both eyes was the birth of spectacles.

All that was still needed was the development of a convenient frame. The rivet frame was the first idea and was so successful that only modest changes were made for nearly 200 years. In the Venetian trade regulations of 1284 there was no mention of spectacles. But sixteen years later, on April 2 of the year 1300, in a further paragraph, the *roidi da ogli* are mentioned, and it was stipulated that they be made, like several other

high-quality glass objects, only from the newly invented *cristallum*. That was a clear indication that the High Court was aware of the enormous potential of the spectacles for the glass trade of Venice. Therefore the invention must have been made shortly before that year, possibly in 1285–1290. From this insight we can assume that the invention almost certainly took place in Venice.



The Development of Spectacles in the Later Middle Ages and in the Renaissance

The first negative spectacles

As we noted above, breaking glass balls produced many meniscus-shaped glass plates. To make positive lenses for presbyopic eyes, one needs to grind only the concave side plane. But it was also easy to see that by grinding the convex side plane, one would get negative lenses for myopic eyes. Therefore, the making of negative glasses was no more complicated than making positive ones.

Nevertheless, the earliest written documents relating to negative spectacle glasses date only from the middle of the fifteenth century.²¹ One of the documents is a letter dated 21 October 1462, from the duke Francesco Sforza of Milan, to his ambassador in Florence, Nicodemo Tranchedini of Pontremoli. The letter states that he had been repeatedly asked to procure spectacles from Florence because they were of much better quality than spectacles made elsewhere in Italy. He ordered three dozen glasses packed into small cases. One dozen was for younger people, to help them view distant objects (negative glasses), one dozen was for older people, to help them see short distances (positive glasses), and one dozen was for normal eyes (plane glasses).

Four years later, three months after the death of Duke Francesco, there was a request from his son in a letter, dated 13 June 1466 to the same ambassador in Florence, to send him more spectacles according to the following list:

The Development of Spectacles

- ♦ 15 pair of eyeglasses for 30, 35, 40, 45, and 50 years, of the best quality
- ♦ 15 pair of eyeglasses for 40, 45, 50, 55, 60, 65 and 70 years
- ♦ 10 pair for medium sight for young people (negative)
- ♦ 10 pair for distance viewing for young people (negative)

In both of these letters it is obvious that negative spectacles for myopic eyes were regarded as entirely ordinary objects, and ones that spectacle makers would be expected to have in stock.

Although there is no extant documentation concerning negative lenses from an earlier period, this silence is not a sign that they did not exist in the fourteenth century. Because we know now how easy they were to make, the assumption would be that they, too, were manufactured in the fourteenth century. Negative glasses for myopic eyes, even those dating from the sixteenth century, are very rarely found today in collections, but this apparent shortage can be explained by the fact that the demand for them was much less than that for positive glasses for presbyopic eyes. This was probably because nearsightedness is not as common as farsightedness, for the latter condition is the fate of everyone attaining 45–50 years of age. We can therefore assume that the proportion would be around 100 positive glasses to each negative glass, with the possibility none of them even survived.

Spectacle-glass production in northern Italy

Venice's preservation of its monopoly on spectacle glassmaking could not have been sustained for a very long time. As we already know, in 1313 a chronicle mentioned that the monk Alessandro Spina could make spectacles, and was happy to teach the art to anyone who was interested. There were only two difficulties. First was the necessity of blowing a more or less spherical glass ball. Its thickness was critical; if it was too thick, the ball quickly elongated to a pear shape due to its weight. But if it was too thin, when the plane was ground, the resulting plates had much too small a diameter. The second problem lay with the *cristallum*. It was especially important that the material of which the oven was composed came from secondary clay deposits, and that the glassblowers had the necessary natron, and not the potash, which was used north of the Alps, for the melt.

To what extent northern Italian towns had access to Alexandria and to the salt from Wadi en Natrun is not known, but it seems likely that the superior maritime power of Venice was dedicated to preserving this monopoly. The three spectacles from Wienhausen suggest that the Venetians had been successful in this endeavour for at least several decades. Wo₁ and Wo₂ were quite evidently not made from *cristallum*, as their color is too strong—but Wo₃ could have been. But all three were in fact made from sodium glass, as the fine preservation of their lenses proves.

Na₂CO₃ could be made in exactly the same fashion as potash, namely by burning plants, but not trees. But it was necessary to burn plants from the sea, because the burning of seaweed gave salt, which, like potash, diminished the melting point of a glass mixture. Because seawater contains sodium and very little potassium, this salt was nothing more than soda. But unfortunately it came with many pollutants, especially iron in trivalent form, which gave the glass a yellowish tinge. Because the amount of soda gained with this method was not very high, it was always used together with potash in the towns of northern Italy. An example might be the half spectacle from Isenhagen. It has a clear greenish tinge, and the faint devitrification suggests that the glass contains a fairly large amount of potash in addition to the soda.

The glass of the Wienhausen and Isenhagen spectacles was probably melted in one of the northern Italian glasshouses, and not in Venice. It seems that the three spectacles and the single lens in Wienhausen, the half spectacle in Isenhagen, and the four glasses in the book-case in Lüneburg, are the only examples of rivet spectacle glasses from the fourteenth century to have survived in fairly good condition. They were all very probably manufactured in Italy, but because no written sources exist, it is difficult to say how far north of the Alps spectacle glasses were being made at that time.

But there have been other discoveries of rivet spectacles: these have been found in a medieval lavatory hole in the Augustinian monastery in Freiburg (Breisgau-Germany), in London, and in the summer of 2001 in Bergen op Zoom (Netherlands). In some cases no glasses survived, and in others the glasses are completely devitrified and therefore impossible to subject to any optical investigation. It is very likely that lens production in Italy completely fulfilled the need for this useful vision aid during the first 100 years.

But before we delve any further into this history, we should clear up a very old issue. Seventy years ago Vasco Ronchi asked the following question: "If it is now certain that spectacles were invented toward the end of the thirteenth century, what is then the reason that three hundred years passed until the very simple observation was made, that a suitable combination of two lenses magnifies distant objects?" In 1972, this important question was posed again by Lindberg and Steneck.^{22,23} The answers from Ronchi and later from Lindberg and Steneck are very different, and indeed contradictory; none of them fully addresses the crucial reason.

We now know the technique by which these lenses were made, as well as their utmost optical possibilities and resolving power. A lens made with *ball-blowing technology*, even one fashioned by the most skilled glass-blower, would not have had optical capabilities sufficient for a telescope objective with a resolving power exceeding that of the human eye. Now that we have revealed the mystery of the invention of spectacles, we will find the reason for the long wait for the first real telescope that fulfills our definition. We now understand why eyeglasses of the fourteenth century could never provide the solution. The glassblowing technique, as ingenious as it was, was a dead end as far as the invention of the telescope is concerned.

The influence of the invention of book printing upon the development of spectacles

In 1450 in Mainz (Germany) printing books with movable types began with the method invented by Johannes Gutenberg. From that time on, in many German towns, presses were founded, and as early as the fifteenth century books were printed by the thousand. Literacy spread quickly among the bourgeoisie. First, older people learned to read, because they were now able to acquire important printed texts at moderate prices. The result was naturally an enormous growth in the demand for spectacle glasses. Eyeglasses from Italy became more and more expensive, and their delivery increasingly difficult.

And as it is in present day, so it was 500 years ago. If it becomes difficult to obtain a desired product, and if selling it is a profitable matter, we do not have to wait long before copies of the item begin to appear. But a real innovation, and not just a simple copy, was required.

The first spectacle makers in Nuremberg

In the minutes of the Nuremberg council of the fifteenth century, we read that “Anno 1478 Jacob Pfüllmair Parillenmacher” was given civil rights against an amount of 14 florin.²⁴ And in the following years one admission followed the other. From 1478 until 1500, twelve spectacle makers received Nuremberg citizenship. Toward the end of the century, an application was made to the court, the so-called *Rugamt*, to give the spectacle makers’ trade the status of a “geschworn Handwerk,” a sworn trade. But the court ruled against this petition, and ordered that the trade must remain *ein gesperrtes Handwerk*, a “banned trade,” in order to preserve the secret of its manufacture. Therefore spectacle makers were not allowed to practice their trade anywhere other than in Nuremberg.²⁵ It was exactly the same as the situation in Venice.

But we must ask, what was the *secret* of the Nuremberg spectacle makers? Spectacle making had been well known there for 200 years, because the Venetians could not hide their secret forever. Of course we recognize that features of spectacles clearly changed in the last decades of the fifteenth century. The rivet spectacle, made exclusively in Italy during the previous 150 years, soon had serious competition from Nuremberg. The materials of bone and wood from which the rivet spectacles were made nearly disappeared, and were replaced by leather, horn, and especially rolled copper wire. The lens-makers of the sixteenth century developed an innovation in the development of new frames in different trade locations, particularly in Nuremberg and later in Regensburg. But the secret so jealously preserved in 1498 was not to be found in the new frames, because these could be seen and copied by anyone.

The secret was found in a completely new method for making the lenses themselves. As noted above, for lenses made with the blowing method, the convex surfaces were part of a blown glass ball, while the plane surfaces were ground. The grinding technique still remained at the same level as in Antiquity. The Nuremberg spectacle makers solved this problem in exactly the opposite way. They cut round glass discs from window glass plates, which they acquired from Bohemia and Bavaria as *Waldglas*, a green-tinged potash glass. These plates were made by the old technique of blowing a cylindrical tube, cutting it along the side, and opening the still hot and pliable molten glass on a plate. This technique was already used in Roman times, and had been well known for more

than 1,000 years. They then hammered a copper plate into a concave mold in the shape of the convex surface of the spectacle. The concave curvature of the mold was measured with a stencil that was made with the help of a pair of compasses. This concave mold was then fixed at the axle of the grinding machine and the plate disc was ground at one of its two surfaces in this mold. In this simple way they avoided the difficulties associated with the ball-blowing process—the plane side remained unground.

We see then that the Nuremberg spectacles of the final decades of the fourteenth century looked quite different from the Italian ones. For the rivet spectacles, the convex side was blown and not ground, and the plane side was ground. But in the Nuremberg spectacles the convex surface was ground and polished, while the plane surface remained unground.

The new technique of grinding in concave molds, invented first by the Nuremberg spectacle makers, needed different concave molds for different powers of glasses. The revolutionary improvement was that ground convex surfaces, if carefully made, could attain much greater optical precision. In the ball-blowing technique, the precision remained very limited. But in the mold-grinding technique, the outcome depended mainly on the precision of the concave mold. The new Nuremberg technique therefore offered enormous possibilities for higher-quality spectacle glasses, a development completely incompatible with the old Venetian method.

But further investigation shows that in the first decades the Nurembergers did not fully realize the true potential of their new method. In the late fifteenth century, the quality of Nuremberg spectacles did not really surpass that of their competitors in Italy. The main obstacle was the fact that the plane surfaces remained unworked, and were therefore just as defective as the convex surfaces of the Italian glasses. But in the early sixteenth century the Nurembergers became aware of this drawback, and from then on they always ground both surfaces.

This change was the starting point in the improvement of the quality of spectacle glasses, but only in principle, for this period also saw the emergence of eyeglasses as mass-produced items. The more the demand increased, the more frequently spectacle makers opened shops, trying to oust their competitors with even lower prices. Quality, as a consequence, was also lowered. Most of the glass used was potash glass, the so-called Waldglas. This glass was strongly affected by the humidity of the air and devitrified completely after some decades (figure 39). Only for higher-

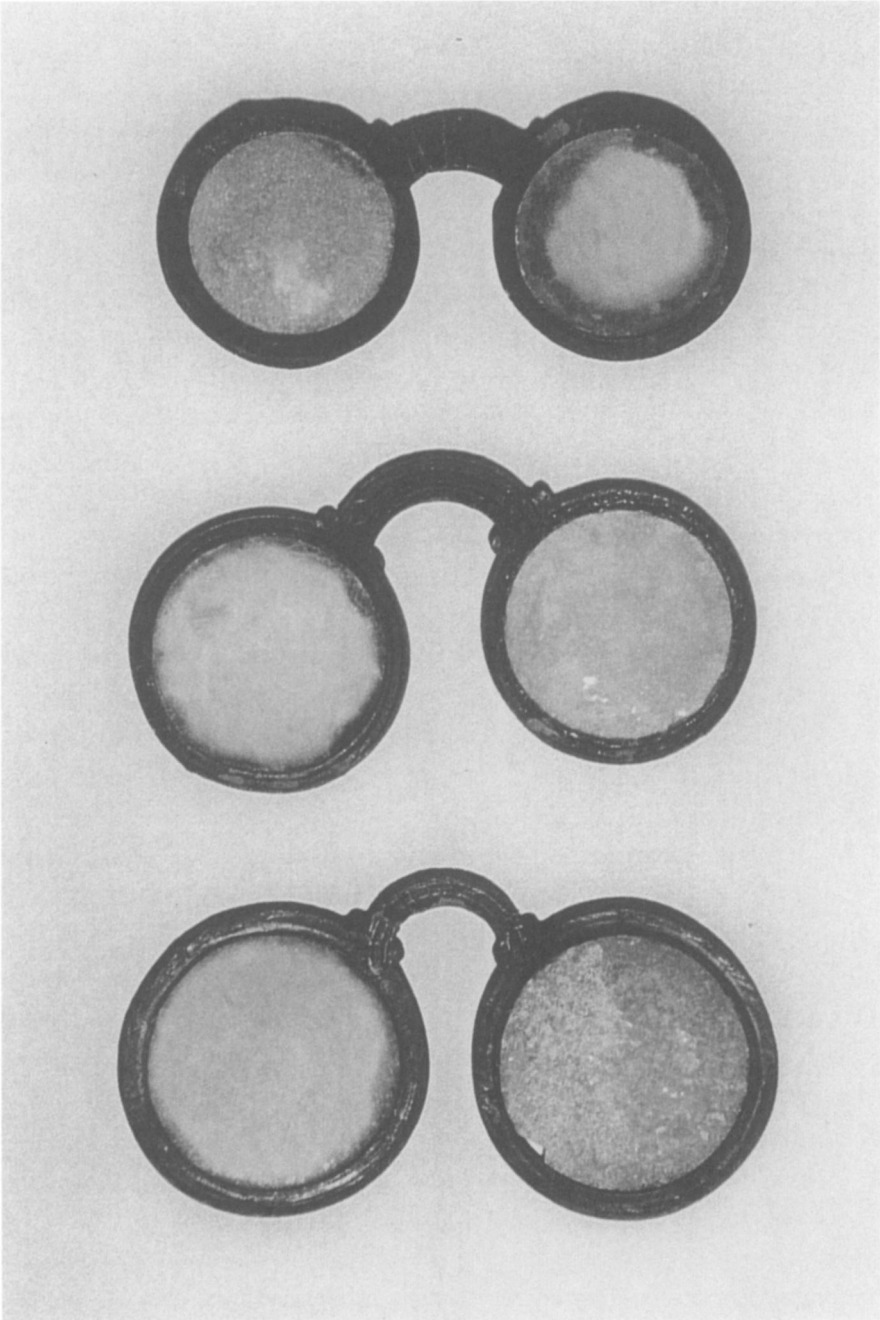


FIGURE 39. Three of a total of eight spectacle glasses from the Nuremberg humanist Willibald Pirckheimer (1470–1530). All of the lenses are completely devitrified and optically useless. Wartburg Museum near Eisenach (Germany).

quality orders did the Nurembergers use sodium glass imported from Italy, especially from Venice.

Now we will examine two Nuremberg spectacles, made with Italian sodium glass in the late fifteenth century. They have unworked plane surfaces, and because this type was not manufactured for an extended period, they are rarely found today.

Specimen T04 is a spectacle with a frame made from whalebone with unground plane surfaces (collection of U. Timm). Diameter of the glasses is 34 mm. The lenses are of sodium-potash glass and have a greenish tinge with numerous small bubbles, the largest ones 0.3 mm, and many striates. Both glasses are plano-convex. The plane surfaces are very clear without any remnants of grinding, but they are also very irregular and far from being optically flat. On the convex surfaces we note numerous faint dark points as remnants of the grinding process. Both convex surfaces have been slightly aspherically ground with increasing curvature toward the rim. Radius of curvature: glass $r_1 = 276$ mm, glass $r_2 = 272$ mm; approximate focal length: $f = 510$ mm = 2 diopters.



FIGURE 40. Ronchi test, left glass, T04.



FIGURE 41. Ronchi test, right glass, T04.

The strong irregularities in the Ronchi lines for specimen T04 (figures 40 and 41) are the result of the unground plane surfaces.

Specimen WCo1 is a leather-framed spectacle (Wellcome Collection, Science Museum London, Inv. No. A681540). Diameter of the glasses is 32 mm. Both glasses are clear with a yellow tinge, with many slightly elongated small bubbles and many striates. Both glasses are plano-convex. Plane surfaces are completely clear with no remnants of a grinding pro-



FIGURE 42. Left glass Ronchi test, spectacle WCo1.



FIGURE 43. Right glass Ronchi test, spectacle WCo1.

cess. Convex surfaces are aspherically ground. Many faint dots, remnants of grinding, are visible. Focal length: $f = 385 \text{ mm} = 2.6$ diopters.

The telescope test

To determine if the lenses would be useful as telescope objectives, every glass has to be combined with a (modern) lens of 75 mm focal length, which serves as an eyepiece. Using that combination, an ophthalmological

test plate (figure 44) was photographed at a distance of 6m. The two bottom lines of the test plate remain unresolved by the naked eye. Therefore a real telescope must resolve, at the very least, the last two lines.

The Ronchi tests of specimen To4 (figures 40 and 41) indicate some improvement in comparison with the Ronchi test of the rivet spectacles discussed in the previous chapter. But if we try to use To4 with a (modern) eyepiece lens as a telescope, the image

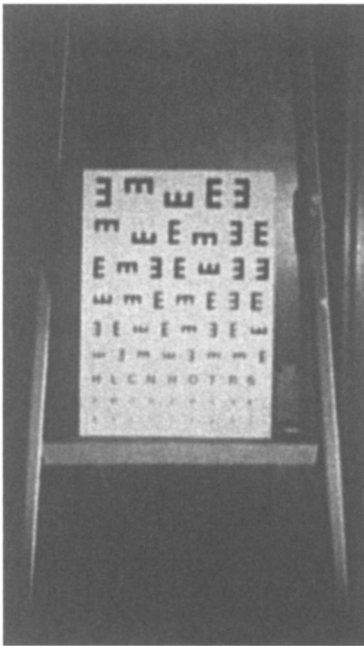


FIGURE 44. Ophthalmological test plate used for telescope test, as seen with the naked eye.

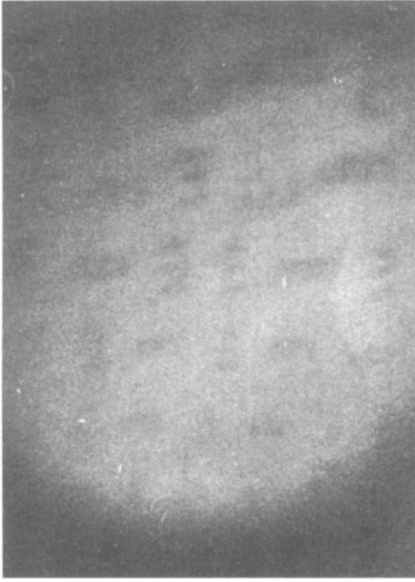


FIGURE 45. Telescope test, left glass, spectacle T04.

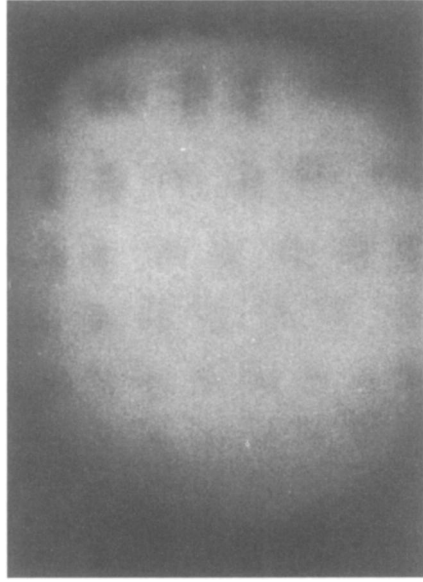


FIGURE 46. Telescope test, right glass, spectacle T04.

of the test sheet shows only blurred shadows (as in figures 45 and 46). WCo1 is even worse. Both glasses are characterized by strong astigmatism, so their Ronchi tests (figures 42 and 43) produce results no better than those from a rivet spectacle, and no telescope test is possible.

♦ ♦ ♦

We do not know to what extent the new spectacle frames were developed in either Nuremberg or Italy. The Nuremberg opticians started this important innovation, but it is very probable that their busy Italian competitors also made significant contributions to the new design. It is also certain that the Italians soon copied their rivals' style of spectacle frames, because toward the end of the fifteenth century the Italian rivet spectacle completely disappeared.

It is somewhat surprising that we can find spectacles in the Nuremberg style, that is, made with leather or rolled copper wire, which were manufactured in Italy with the old glass-ball technique.

The reason that Italians still relied on this obsolete technique as late as the early sixteenth century may be that the Nurembergers were able to keep their secret for a very long time. Another possibility is that the Ital-

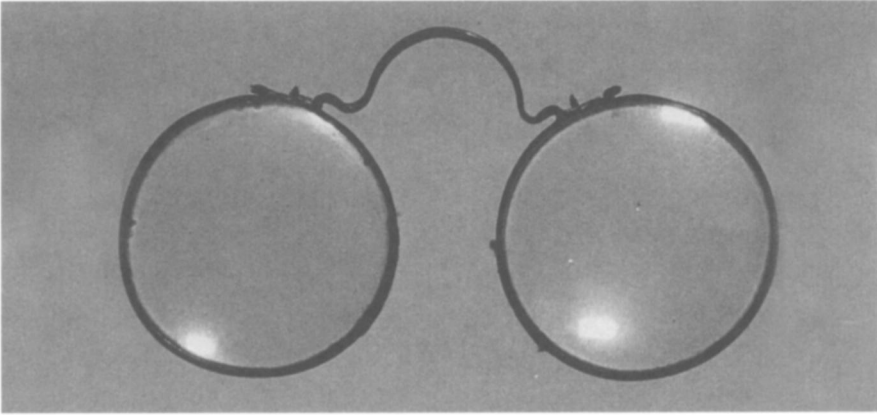


FIGURE 47. Copper wire-framed spectacle, T07 (collection of U. Timm).

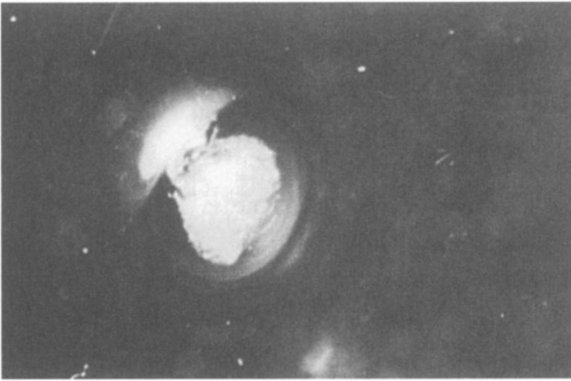


FIGURE 48. Detail, right glass of T07.

ians were reluctant to abandon a method that had been successful for the last 200 years.

The three spectacles illustrated and discussed in the following pages are examples found by the author which appear to have been made in Nuremberg, but with the blown glasses typical of the old rivet spectacles. Therefore, they most likely were made in Italy.

Example T07 is a spectacle with a frame of copper wire (figure 47). Diameter of the glasses in T07 is 34 mm. The soda-potash glass has a faint greenish tinge and many very small bubbles. Both glasses are asymmetrically biconvex. The stronger convex surfaces are part of a glass ball. Glass is totally clear and shows no remnants of grinding.

On the more strongly convex surface of the right glass of T07 (figure 48), we recognize clearly a striate that crosses the lens. Near the

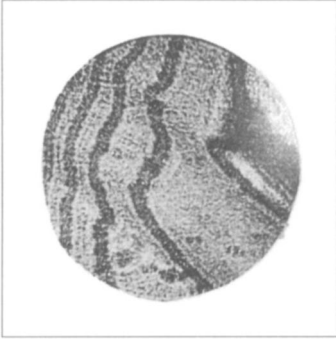


FIGURE 49. Ronchi test, T07 (left glass). Focal length: $f = 185 \text{ mm} = 5.4 \text{ diopters}$.

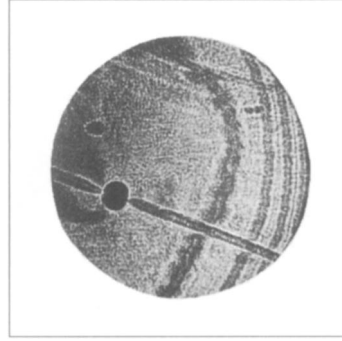


FIGURE 50. Ronchi test, T07 (right glass). Focal length: $f = 214 \text{ mm} = 4.7 \text{ diopters}$.



FIGURE 51. Telescope test, T07 (left glass).

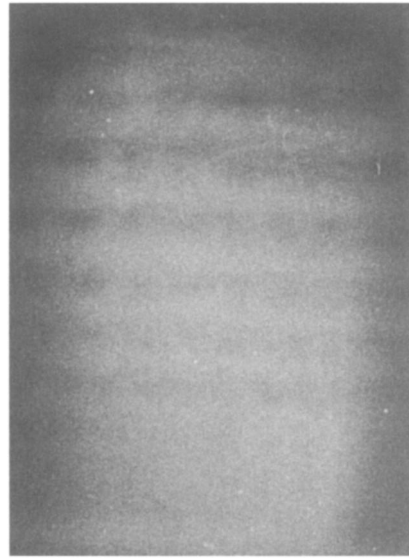


FIGURE 52. Telescope test, T07 (right glass).

middle of the glass there is a remarkable raised dot, easy to detect with the fingertip.

In the Ronchi test of spectacle T07 (figures 49 and 50) we see very distorted Ronchi lines. Therefore in the telescope test, the image of the test sheet is completely blurred and unreadable.

Specimen W04, a leather-framed spectacle from the nuns' choir in the Wienhausen monastery (see figure 22, chapter 5) has a tooled H at the

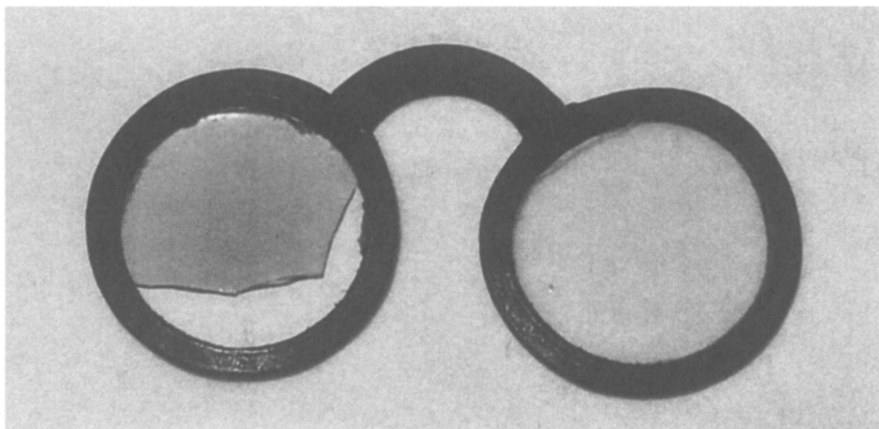


FIGURE 53. W04, leather-framed spectacle from the nuns' choir of the Wienhausen monastery.

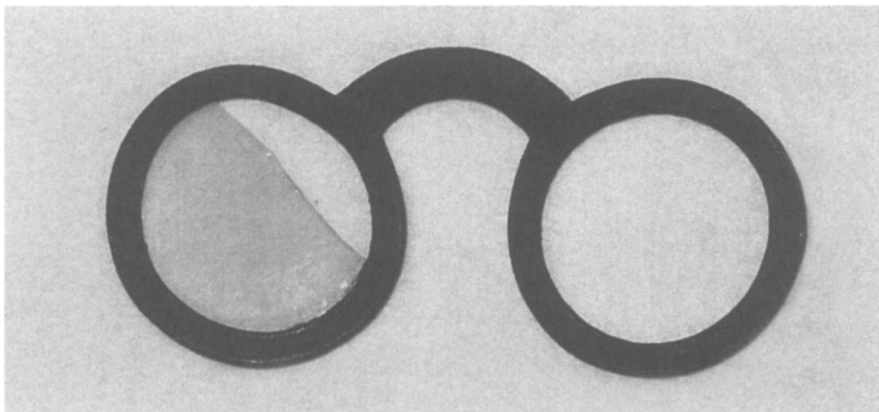


FIGURE 54. W05, leather-framed spectacle from the nuns' choir of the Wienhausen monastery.

bridge. The right glass is nearly colorless, with only a faint yellow tinge. It is asymmetrically biconvex. The more strongly convex surface is blown. Lens is slightly devitrified and therefore not clear. The weaker convex surface is ground and well polished. There are a few remnants of polishing in the central region of the lens. Radius of curvature: $r_1 = 176 \text{ mm}$, $r_2 = 4765 \text{ mm}$.

The left glass in figure 53 does not belong to this spectacle and will be analyzed in the following chapter (see figures 60 and 61, chapter 7). Because the glass of the right lens is insufficiently transparent, Ronchi and telescope tests of it are not possible.

The Development of Spectacles

Specimen W05 is another leather-framed spectacle from the Wienhausen monastery. Its one surviving glass has a very faint greenish tinge with approximately 10 air bubbles. The surface is convex, without remnants of grinding. The plane surface has many fine dots from grinding. Radius of curvature: $r_1 = 234$ mm, $r_2 = 71500$ mm. Due to the glass's extreme astigmatism, Ronchi and telescope tests are not possible.

♦ ♦ ♦

These types of spectacles, in which one of the surfaces remained unground, completely disappeared in the first decades of the sixteenth century. From then on, in Nuremberg, Italy, and other centers of spectacle production, such as France and England, both surfaces were ground. But before we discuss in detail this further development, we will have to examine a serious problem.



Evolution of the Modern Lens-Grinding Technique in the Sixteenth Century

The dating of the spectacles

Our investigations are approximately at the beginning of the sixteenth century. But the word *approximately* should be emphasized. It is well known to every serious spectacle collector that the assignment of a date to a spectacle is possible only in the rarest of circumstances. By and large, we must be content with a rather broad time range. The spectacle frames that are shown here were made with only a few changes from the second half of the fifteenth until the early eighteenth century. For leather spectacles, we occasionally find, sometimes already in the early sixteenth century, examples stamped with a master's sign. That feature can restrict the time estimation (see for example the Pirkheimer spectacles, figure 39 in the preceding chapter). But most of the spectacles that have survived offer no clear hint of the manufacturing date on their frames.

The author's investigations clearly showed that only with a complete assessment of all glass parameters, as with the foregoing examples, would a reliable chronological assignment be possible. For example, the spectacles in chapter 6 could be classified, based upon an examination of their frames, from the early sixteenth until the early eighteenth century. But the investigation of their optics indicates that they can be dated at latest to the first decades of the sixteenth century. In this case we are aided by a fairly rare circumstance, which fully confirms this estimated dating. The Wienhausen Monastery, with its "holy blood relic," was a well-known place of pilgrimage. The two leather-rimmed spectacles Wo4 (figure 53) and Wo5 (figure 54) were found, like the rivet spec-

tacles, in the dust under the wooden floor of the nuns' choir. They were put there by pilgrims, along with more than 1,000 other small pieces collected over the course of two hundred years, as a modest sacrifice. They certainly did not, as is sometimes claimed, fall into the slit between the wooden planks by chance. This would have been impossible because of local circumstances.

This kind of deposition or offering was no longer available when Wienhausen ceased to be a destination of pilgrimage. That was when Duke Ernst von Braunschweig-Lüneburg introduced the Reformation. This dramatic change started in 1527 and ended in 1530. Most of the nuns left this cloister and found admission elsewhere; from then on the old monastery became the dwelling place for "ladies living alone," a status preserved even today. We can therefore conclude that all discoveries made in the nuns' choir date from before 1530. This is in agreement with our first estimation, but was derived by a very different line of reasoning.

Improvements in lens-grinding techniques in the sixteenth century

The author examined a total of 57 spectacle lenses, dating from approximately 1500 to 1620/50. They belonged to many different private collections and museums, and 16 of those examples will be discussed in detail in this chapter.

The 16 glasses are a representative choice of the 57, and are characteristic of glasses from the sixteenth and early seventeenth centuries. But they are a minority, as all of them were made from real sodium and sodium-potash glass, which was introduced from Venice by the Nuremberg and Regensburg spectacle makers for more prosperous customers.²⁶ It seems that none of the glass spectacles made with the Bohemian potash glass survives today in good optical condition.

All of the 57 glasses are ground on both surfaces, as were the glasses of the three examined leather spectacles from Wienhausen (all before 1530). It was recognized fairly quickly that those glasses with only one surface ground and polished, and the other merely produced by blowing, are of a very low quality. Therefore we can assume with considerable certainty that glasses made by the ball-blowing technique, and with an unground plane surface, disappeared shortly after 1500.

This knowledge is important in helping to answer the question of when lenses with sufficient quality for telescopes became available. In contrast to the older lenses, the quality of lenses where both surfaces are ground is not as dependent on the skill and the care of the grinder. Nevertheless, we can see from the enormous variation in the quality of the lenses that the skill and care of the grinders remained a very important factor in the result. Several spectacles with both surfaces ground are illustrated and described below and on the following pages.

SPECIMEN WO7. The right glass in W07, a leather-framed spectacle from Wienhausen monastery (figures 55 through 59), has a noticeable green tinge and several elongated bubbles. It is of sodium-potash glass and is

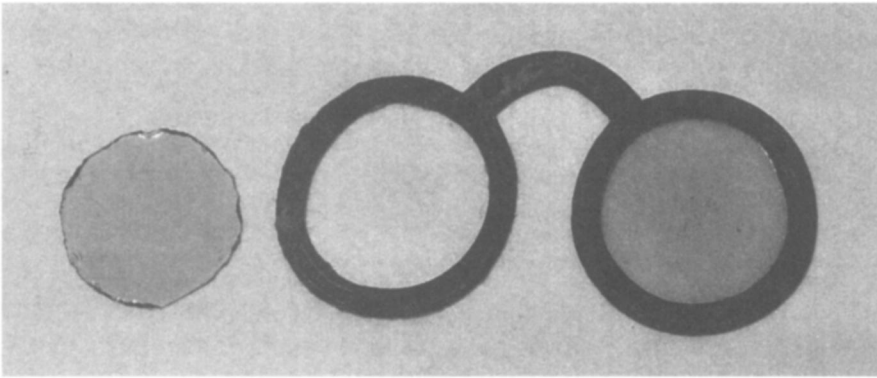


FIGURE 55. Leather-framed spectacle W07, with unrelated glass W07L at left, from the nuns' choir of the Wienhausen monastery.



FIGURE 56. (above) Ronchi test of left glass, W07L (not actually part of spectacle W07).



FIGURE 57. (above) Ronchi test of right glass, W07.

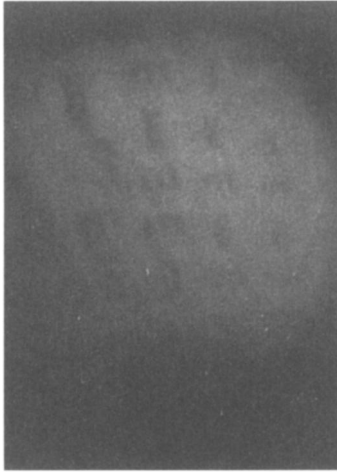


FIGURE 58. Telescope test of left glass of W07L (not actually part of spectacle W07).

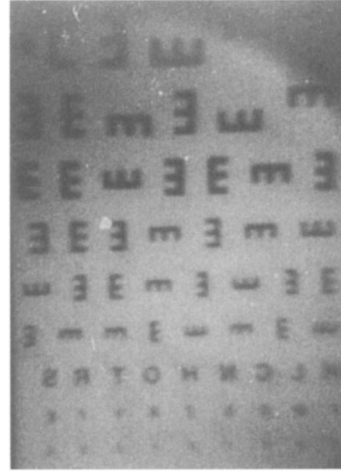


FIGURE 59. Telescope test of right glass of W07.

asymmetrical and biconvex. Radius of curvature: $r_1 = 228$ mm, $r_2 = 341$ mm; focal length: $f = 249$ mm = 4 diopters; refracting index: $n = 1.549$.

The separate left glass (W07L) in figure 55, not actually a part of W07 but of a similar type, has a discernible greenish tinge with many elongated bubbles and long, parallel striates. Diameter: 31 mm; radius of curvature: $r_1 = 244$ mm, $r_2 = 2380$ mm; focal length: $f = 410$ mm = 2.8 diopters. It is of sodium-potash glass, and is approximately plano-convex.

SPECIMEN W04L. Figures 60 and 61 show Ronchi and telescope tests of the single glass W04L, the glass pictured to the left of spectacle W04 (figure 53 in chapter 6) and which does not actually belong to W04. The glass has a strong green-blue tinge, and is approximately symmetrically biconvex. Radius of curvature: $r_1 = 329$ mm, $r_2 = 311$ mm; focal length $f = 216$ mm = 3.4 diopters.

SPECIMEN T09. Specimen T09 (figures 62 through 66) is a spectacle with a whalebone frame from the collection of U. Timm. Both glasses have a green tinge and many very small bubbles. Sodium-potash glasses are poorly polished. Radius of curvature, left glass: $r_1 = 285$ mm, $r_2 = 285$ mm; focal length $f = 263$ mm = 3.8 diopters. Radius of curvature, right glass: $r_1 = 297$ mm, $r_2 = 294$ mm; focal length $f = 274$ mm = 3.6 diopters.



FIGURE 60. (above) Ronchi test of the separate left glass of specimen W04L (see figure 53 in chapter 6).

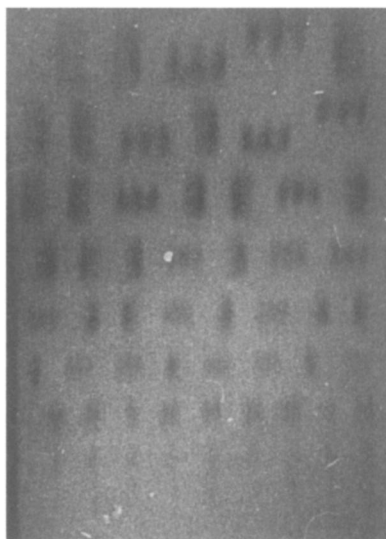


FIGURE 61. (right) telescope test of W04L.

SPECIMEN T12. Specimen T12 (figures 67 through 71, from the collection of U. Timm) is a jointed or hinged spectacle with a horn frame, engraved on the outer edges of the lenses “Bernardo Picinelli” (left), and “in Venezia” (right). It has been preserved with its case (figure 67). The glasses have a faint yellow tinge and few bubbles. The right glass is extremely full of striates. Glass diameter: 34mm. Radius of curvature, left glass: $r_1 = 373$ mm, $r_2 = 492$ mm; focal length: $f = 393$ mm = 2.5 diopters. Radius of curvature, right glass: $r_1 = 370$ mm, $r_2 = 514$ mm; focal length $f = 398$ mm = 2.5 diopters.

SPECIMEN WMO3. This specimen is a wire-framed spectacle from the collection of I. and W. Weismüller (figures 72, 73, and 74). The left glass is nearly colorless, but contains plenty of small, elongated bubbles and striates. The right glass is faintly yellow-brown, with few bubbles but many striates. Both lenses are sodium glass. Radius of curvature, left glass: $r_1 = 617$ mm, $r_2 = 571$ mm; focal length: $f = 549$ mm = 1.8 diopters. Radius of curvature, right glass: $r_1 = 672$ mm, $r_2 = 599$ mm; focal length: $f = 586$ mm = 1.7 diopters. The left glass of Wmo3 exhibits such extreme astigmatism that no Ronchi test or telescope test were possible.

SPECIMEN WMO6. A leather-framed spectacle from the collection of I. and W. Weismüller (figures 75 through 78), specimen Wmo6 has a clear

(Text continues on page 77)

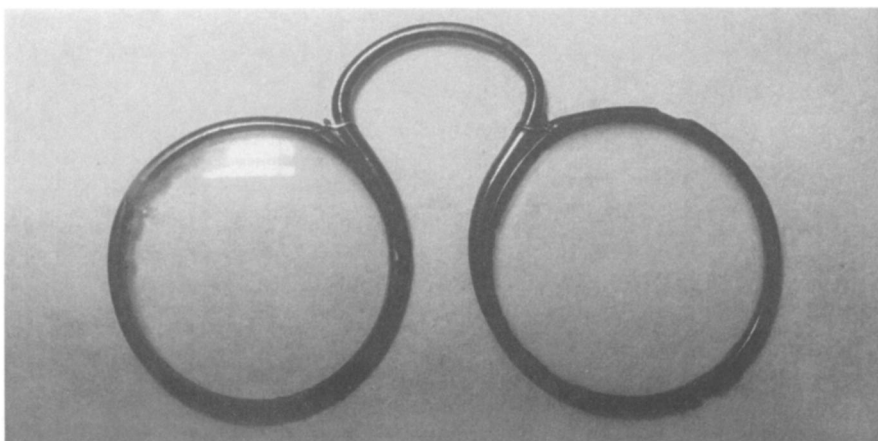


FIGURE 62. Whalebone-framed spectacle, T09 (collection U. Timm).



FIGURE 63. Ronchi test, left glass of T09.



FIGURE 64. Ronchi test, right glass of T09.

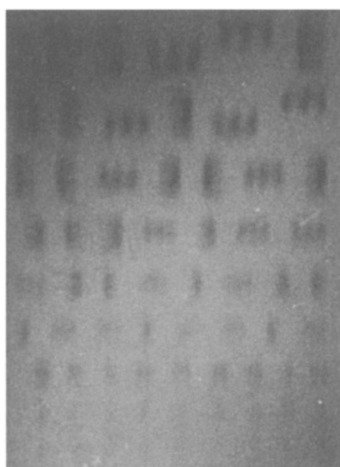


FIGURE 65. Telescope test, left glass of T09.

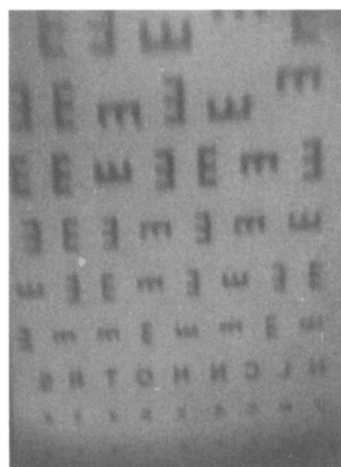


FIGURE 66. Telescope test, right glass of T09.

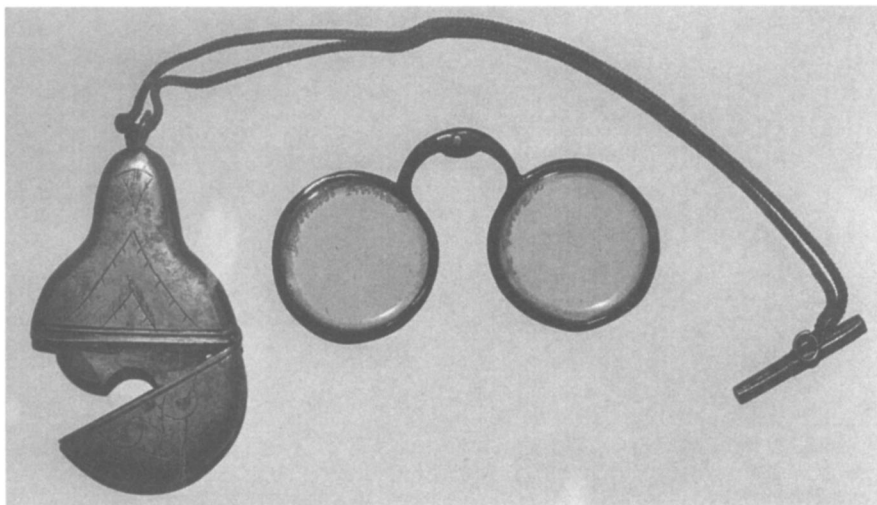


FIGURE 67. Jointed spectacle with horn frame, T12 (collection of U. Timm).



FIGURE 68. Ronchi test, left glass of T12.

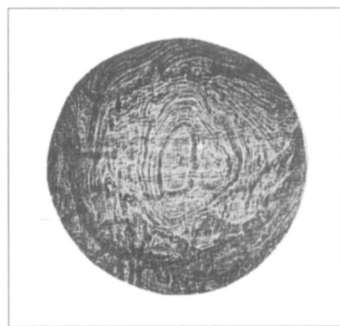


FIGURE 69. Ronchi test, right glass of T12.

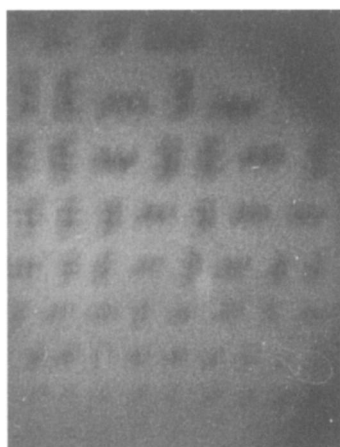


FIGURE 70. Telescope test, left glass of T12.

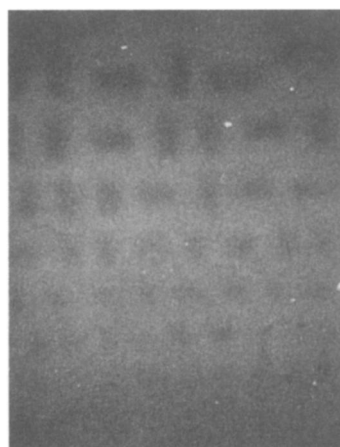


FIGURE 71. Telescope test, right glass of T12.

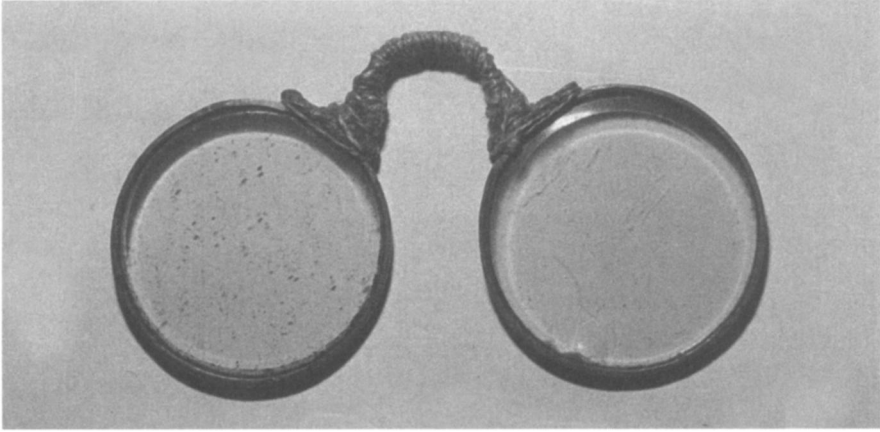


FIGURE 72. Wire-framed spectacle, Wmo₃ (collection of I. and W. Weismüller).



FIGURE 73. Ronchi test, right glass of Wmo₃.

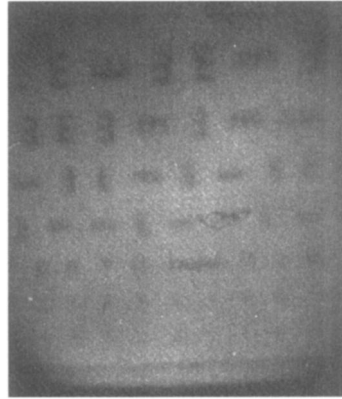


FIGURE 74. Telescope test, right glass of Wmo₃.

left glass with a green tinge and no bubbles. The right glass has a faint grey color and a few bubbles. The lenses and rims are oval. Radius of curvature, left glass: $r_1 = 188$ mm, $r_2 = 189$ mm; focal length: $f = 174$ mm = 5.7 diopters. Radius of curvature, right glass: $r_1 = 335$ mm, $r_2 = 257$ mm; focal length: $f = 269$ mm = 3.7 diopters. Due to strong astigmatism in the right glass, no telescope test was possible.

SPECIMENS BHO1 AND BHO2. These are two examples of “slit-bow” spectacles—the arched nose-pieces are carved with slits—both made of horn, from the Museum-Boerhaave in Leiden, the Netherlands (figures 79 through 86).

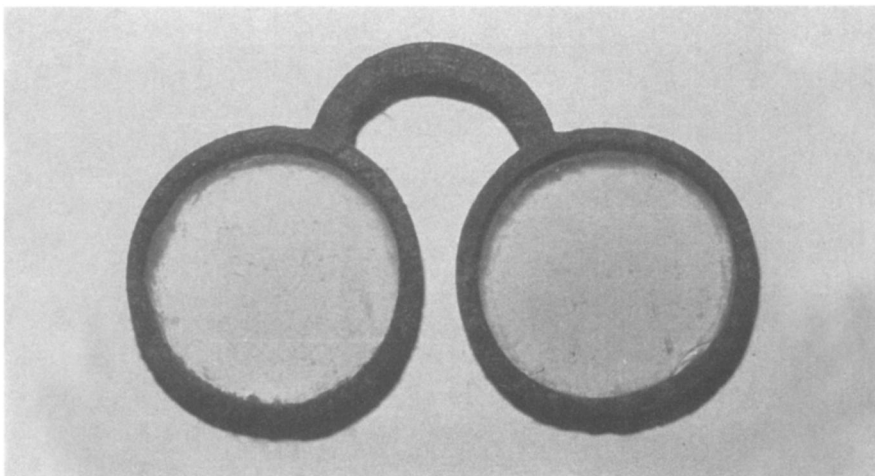


FIGURE 75. Leather-framed spectacle, Wmo6 (collection of I. and W. Weismüller).



FIGURE 76. Ronchi test, left glass of Wmo6.

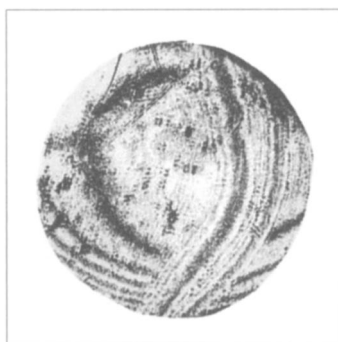


FIGURE 77. Ronchi test, right glass of Wmo6.

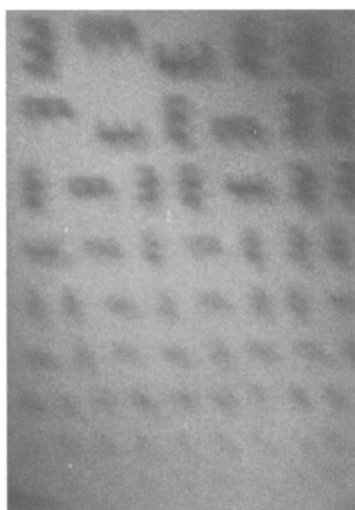


FIGURE 78. Telescope test, left glass of Wmo6 (due to astigmatism, no telescope test was possible for right glass).

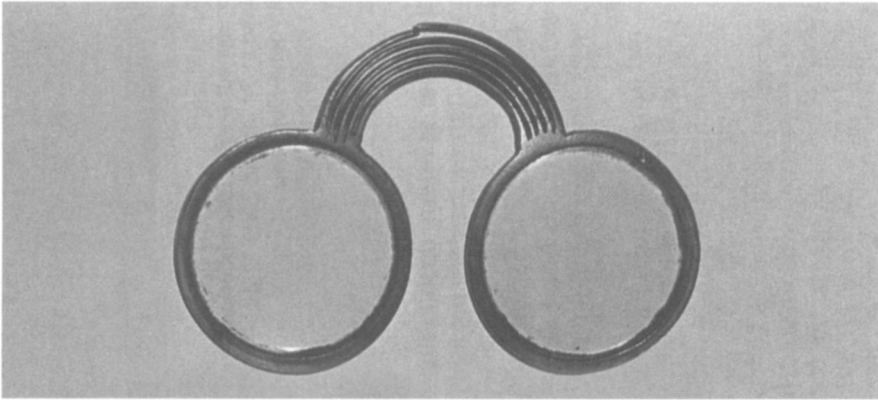


FIGURE 79. Slit-bow spectacle made of horn, Bho1 (Museum-Boerhaave, Leiden, Netherlands, Inv. No. 18927).

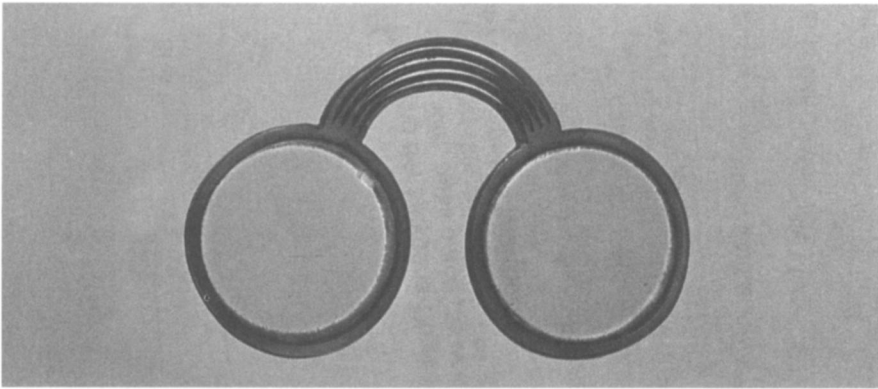


FIGURE 80. Slit-bow spectacle made of horn, Bho2 (Museum-Boerhaave, Leiden, Netherlands, Inv. No. 12557).

Both lenses of Bho1 are a faint yellow color, with some small, elongated bubbles and many grinding holes and unpolished scratches. Diameter of glasses: 32mm; focal length: $f = 340 \text{ mm} = 2.9$ diopters.

The glasses of Bho2 have a faint yellow-green tinge, with several small, elongated bubbles. Diameter: 31 mm. Focal length: $f = 1760 \text{ mm} = 0.6$ diopters. Due to the extreme astigmatism in both glasses of Bho2, no telescope tests were possible.

SPECIMEN T05. Another example of a “slit-bow” spectacle from the collection of U. Timm, specimen T05 is not pictured here. Its glasses have a faint green tinge with few small bubbles. Both glasses are very badly

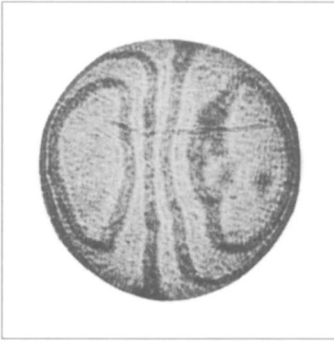


FIGURE 81. Ronchi test,
left glass of Bho1.



FIGURE 82. Ronchi test,
right glass of Bho1.

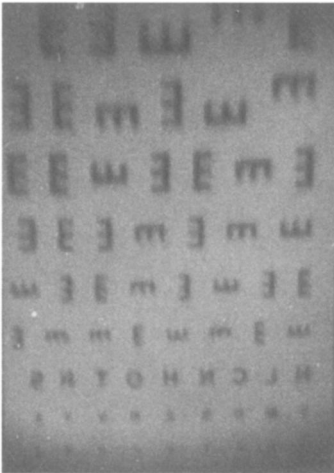


FIGURE 83. Telescope test,
left glass of Bho1.

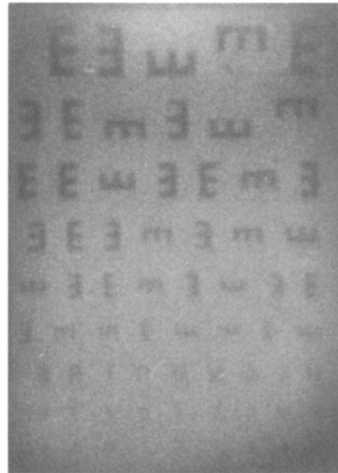


FIGURE 84. Telescope test,
right glass of Bho1.

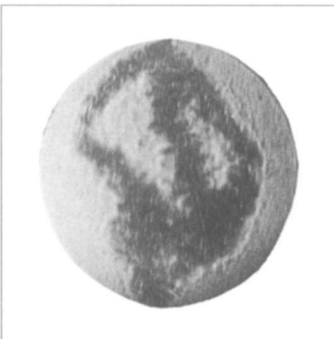


FIGURE 85. Ronchi test,
left glass of Bho2.

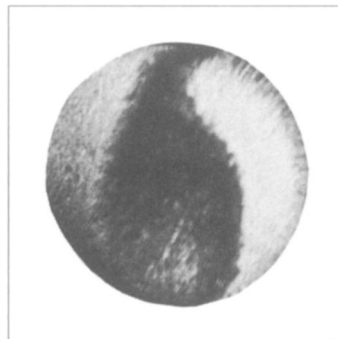


FIGURE 86. Ronchi test,
right glass of Bho2.

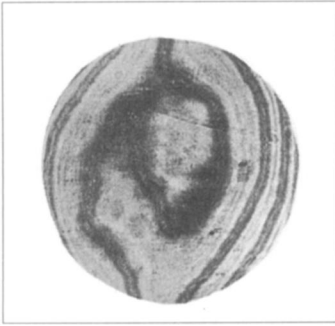


FIGURE 87. (above) Ronchi test, T05.

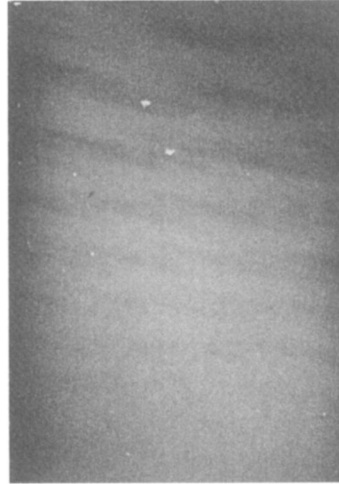


FIGURE 88. (right) Telescope test, T05.

polished. Diameters: 32 mm. Focal length: $f = 233 \text{ mm} = 4.2$ diopters. Only one of the glasses could be tested (figures 87 and 88).

Discussion of results of the examined spectacles

If we look at figure 56 from the Wienhausen spectacle W07, we see that at the inner part of the lens the Ronchi lines are mostly parallel. Only outside of this central region do the aberrations amount to many wavelengths. The reason for this is the most common defect of old lenses, increasing curvature toward the rim.

Although the central area is fairly well made, the lens is unsuitable for a telescope. The surface of the central part is approximately 20 percent of the whole aperture, and therefore the distorted rays from the outer region seriously affect the well-focused rays of the smaller inner region. This lens is remarkable. The image is so clear that with a magnification of 3.3 times, the resolution comes within the range of the human eye (figure 59). It dates from before 1530, and if we compare this test image with those of much later glasses, we realize that well-made glasses would have been possible in the early sixteenth century.

The glasses of T09 are likewise of good quality, especially the right one, as we see in the telescope test (figure 66). But this spectacle is later than W07, and may even date from the early seventeenth century.

Spectacle T12 offers interesting insights into the manufacturing customs of the spectacle makers. The left glass with the maker's name is of

mediocre quality. In the telescope test even the larger letters are difficult to read. But the right glass, signed “in Venezia,” is so extremely full of striae that in the telescope test the letters remain only faint shadows. Striae of such intensity are easy to see under slightly inclined light. We must therefore assume that the grinders ground the lenses in piecework, and without ever checking the quality of the glass.

With the continually growing demand for spectacles, eyeglasses soon became a mass product, and the manufacturers tried to oust their competitors. It would appear that this situation, especially in Nuremberg, became less and less subject to control, and that the High Court of the city quickly became aware of the need for clear trade regulations. The oldest surviving regulation dates from the year 1535, and is the successor of an inextant earlier rule. Today it is found in the Bayerischen Staatsarchiv in Nuremberg.^{26,27,28,29} These developments notwithstanding, in this period Nurembergers were making cheaper, lower-quality spectacles. Their colleagues in Regensburg were making better but more expensive lenses.

Conclusion of the optical examination of these lenses

1. The examined glasses range in date over a period of about 130 years. The earliest one (Wienhausen) dates from approximately 1500 to 1520, the latest from about 1620 to 1630. We did not find any indication that during this time period any principal improvements were made. All the glasses under scrutiny were made for presbyopics, and their refracting power is in the range of 1 to 6 diopters.
2. The quality of the glasses varies enormously. Some are of fairly good quality, but most range from mediocre to poor. And some are so bad that they are, in principle, useless even for spectacles.

The reasons for this broad range in the quality of the glasses will be discussed in the following section.

Lens-grinding techniques in sixteenth-century Italy

We learn more about this technique, in detail, from a written source, *Hieronymi Sirturi Mediolanensis, Telescopium sive ars perficiendi* (Frankfurt 1618). Sirturus offered an elaborate description of the different steps involved

in the process, beginning with the choice of materials, the examination and cutting of the glass, the making of the grinding molds, the washing of the emery, and so on. In chapter III he complained bitterly about the complete “decline of this art.” He said the glasses were never selected for their quality, and that only the cheapest ones were used. The grinding molds were made only with a hammer and not at the turning lathe, and without the use of accurate files. Thus the technique seemed to him no better than the work of a blacksmith.³⁰

This information is entirely in agreement with the results of our examination of the 57 spectacle lenses. We must conclude that even in Venice, with its reputation for high-quality glasswork, the grinding technique had not improved since the middle of the fifteenth century when the Nuremberg spectacle makers invented grinding in concave molds. Even in the second decade of the seventeenth century, the molds were formed only with a round hammer. This crude method resulted in an enormous variation in the quality of the glasses. If the hammered mold was new, then its concave surface was very irregular and the result would be that the sphericity of the lenses was poor.

But if the diameter of the mold was fairly small, for example 5 cm, then the mold would have become more spherical over the course of its use. The result would be a remarkable increase in the quality of the lenses, especially if the turning motion of the grinder’s hand used the whole concavity of the mold and not only a part of it. We know, however, that at least in Nuremberg, because of the distribution of labor and the need to make the product cheaper, they used very large molds and ground lenses with two workers, and therefore with four hands.³¹ The result would not have increased the mold’s sphericity. On the contrary, with this method, the surface of the molds would have become ever more irregular, and the lenses would have been increasingly inferior. In the course of our investigations we found many such glasses. They are all astigmatic and sometimes as bad as the lenses made in the fourteenth century, when the old Venetian ball-blowing method was still used.

Negative lenses in the sixteenth century

In chapter 6 we explained why negative lenses had been invented at the same time as the positive ones. By the middle of the fifteenth century they had become an ordinary article in every spectacle maker’s shop. Sirturus

showed in his treatise “*Telescopium*,” how they were made by grinding the small glass discs on iron cannon balls.³² The sphericity of these projectiles had to be of fairly high accuracy, for otherwise they would not have been able to propel themselves through the barrel of a cannon. Their diameters ranged from a few centimeters to about 25 cm. The refracting power of negative lenses was therefore considerably greater than that of ordinary positive lenses for presbyopics.

That corresponds exactly to the requirements. Despite occasional arrangements where the wearer fixed his spectacles to his cap, during the entire sixteenth century most spectacles were clamped to the sides of the nose. This method of wearing a spectacle was convenient for sitting and reading, but negative spectacles were used for distance viewing by those who were walking or riding. As an example, we know that Gustav Adolph, the King of Sweden, who was very nearsighted, always used a small spy-glass of 2 to 3 times magnification. A spectacle worn on his nose would have quickly fallen off.

The discomfort of wearing negative spectacles, and the reasons already explained in chapter 6, lead us to believe that even in the sixteenth century, negative lenses were made in much smaller quantities and had a remarkably higher refracting power than positive lenses.



Written Sources of the Sixteenth Century Concerning the Combination of Two Spectacle Glasses

IN OLDER LITERATURE we occasionally encounter references to a combination of two lenses, and the magnification for distant objects of such an arrangement. A complete compilation with a detailed discussion of all such writings is found in *The Invention of the Telescope* by Albert van Helden.³³ The texts are not repeated here, but are used only to explain their connection with our investigations.

The earliest mention of such properties of “glasses and crystals” is found in *Opus majus* (approx. 1267), from the Franciscan monk Roger Bacon. He explained, for example, the magnifying effect of a crystal hemisphere if it were placed with its flat surface over some writing. But that object was nothing more than the “reading stone,” which was already known several hundred years prior to Bacon’s time in the monastery libraries. Bacon also wrote, “. . . thus from an incredible distance we might read the smallest letters . . . owing to the magnitude of the angle under which we viewed them . . . In this way a child might appear a giant and a man a mountain. . . .”

Everyone familiar with medieval texts knows that accurate statements are sometimes mixed in with pure fantasy. Bacon’s remarks on the properties of the reading stone are absolutely correct, but if he tells us about the magnifying power of lenses for distant objects, this cannot be taken as proof that it is the result of a correct combination of two lenses. There is not the slightest hint that such lenses existed in Bacon’s time, and nowhere in his book does he mention a combination of two lenses. Some authors

have argued, moreover, that Bacon did not do the experiments himself with crystal lenses,³⁴ and that his ideas were stimulated by Alhazen, since it is known that Bacon read the *Opticae thesaurus*.

For the next 200 years we hear nothing more about magnifying effects of glasses for distant objects. The sole exception would be the reference of Leonardo da Vinci to “make glasses to see the moon larger.” But this situation changes in the first half of the sixteenth century. We find what is probably the earliest mention in the Latin-language *Homocentrica* (Venice, 1538, p. 18v) by Girolamo Fracastoro. Here we read “. . . if anyone looks through two spectacle lenses, one placed on top the other, he will see everything much larger and closer.” This short text is very clear. There is no doubt that Fracastoro was describing correctly the magnifying effect on distant objects, if two lenses are put at an appropriate distance from each other. That is the first obvious mention of a telescopic system. But whether this telescopic system is a real telescope—according to our definition—is a completely different question.

Some years later we find other mentions, although most of the references are unclear. Examples are Robert Recorde in *The Pathway to Knowledge* (London, 1551, pp. 7 and 8), or John Dee in *The Elements of Geometrie* (London, 1570). There is also some limited information by Giovanbattista della Porta in *Magia Naturalis* (Naples, 1589), a conglomeration of all the curiosities known at his time. He mentions the possibility of magnifying distant objects with a combination of two lenses. He wrote that he occasionally helped some friends with such a construction for better seeing. Some attention has also been directed, in recent years, to Leonard and Thomas Digges’ *Pantometria* (London, 1571). But of special interest is William Bourne’s *Treatise on the Properties and Qualities of Glasses for Optical Purposes* (1585). Leonard and Thomas Digges had written that “. . . marvellouse are the conclusions that may be perfourmed by glasses concave and convex of circular and parabolical fourmes . . .” They also described how with such glasses they could see towns and villages very far away and small, or very near and big. Much more detailed is William Bourne’s *Treatise*. He describes the making of a “perspective glass” in chapter IV and gives directions to make the eyeglass. It was a concave mirror “. . . and the glass must bee concave inwardes, and well pollyshed of the hollowe or concave syde: and then the foylle must be layde on that syde that doth swell, as a hyll, and bosse outwards . . .”

Translated into modern English, Bourne described how to cover the segment of a blown glass ball at the convex outside with quicksilver and tin. This technique was popular at that time and was used to make reflectors for lanterns. In chapter V he describes the making of the lens: "Then we must prepare very cleare, and white Glasse that may be rounde, and beare a foote in diameter; as fyne and white Venice Glasse. And the larger the better . . ." And some lines later: "And for that if the Glasse bee very thicke, then it will be hynder the sighte. Therefore it must bee grounde untill that the myddle thereof bee not above a quarter of an ynche in thickness: and the sydes or edges very thynne, and so polysshed or cleared."

This construction of a telescopic system is unusual. A concave mirror is used as the eyepiece and there is also a front lens. The front lens had a diameter of one foot, which was extraordinarily large, and a thickness of only 6 mm, which was very thin. If we assume a refracting index of 1.53, these dimensions would lead to an approximate focal length of 3.5 m, had the lens had something like a focus. The construction is historically interesting and very informative. Basic considerations make it clear that with a long focus lens as the objective and a short focus concave mirror as the eyepiece, it would be possible to create a magnifying telescopic system. But anyone who is familiar with the problems of practical optics realizes quickly, that such a lens, made in the second half of the sixteenth century, even by the most skilled spectacle maker, would not come close to producing a recognizable image at the focal plane. The conditions are not so demanding for the mirror, which was used here as the eyepiece, because the field of vision is in the range of only a few millimeters (see chapter 5).

On the basis of the *Treatise* and further correspondence from Bourne, we can see that he conducted many experiments with mirrors and lenses. He was trying to find the rules of optical depiction of near and far objects, with the clear goal of making an instrument that he could use to see distant objects with more detail. But then we hear nothing more of Bourne, and there does not seem to be any other indication that he was ever successful in this venture. It is of interest that at the same time the Venetian mathematician Ettore Ausonio (approx. 1520 to 1570), conducted similar experiments with mirrors and lenses with exactly the same goal.³⁵

At this point we have to ask what Bourne really made. We are certain that he made a telescopic system, in the described manner, but not be-

fore writing his *Treatise*. After great disappointment with his failure, he surely would not have described it in such detail in his book. But we are also certain that this instrument was constructed on the basis of prior experiments, and was not merely the product of fantasy. Therefore we must conclude that Bourne made such an instrument, with a spectacle glass as the objective. If the spectacle glass had been of good quality it would have been possible to clearly see magnified distant objects with it. Why Bourne recommended making such a large lens, condemning his first idea in this way, can be answered only in conjectural fashion. He could have assumed that the resultant lack of recognizable features in the smallest details was due to the fact that he had too small a lens. Or if he put his eye at the exit pupil, he could see distant objects filling the whole lens, inclining him to believe that a larger lens would also give a larger image.

The examples of Digges, Ausonio, and Bourne are important because they demonstrate that in the second half of the sixteenth century, scholars made great efforts to understand the phenomenon—that a combination of two lenses, or as in the case of Bourne, a lens and a mirror, could magnify distant objects. They were aware of the enormous potential of such an instrument, and their more clever contemporaries did not regard it as a meaningless toy.

We can now return to the lens tests. If we compare the telescope test of the eight best spectacle lenses—W07, W04L, T09(1), T09(2), T12(1), Wm06(1), Bho1(1), Bho1(2)—with the ophthalmologic test plate (as seen by the naked eye; figure 44), we quickly realize that when these glasses were used as objectives in combination with an eyepiece lens of 75 mm focal length, the magnifying effect was clearly recognizable, although fewer details would have been visible. The naked eye cannot resolve the final two lines at a distance of 6 m. The last legible line reads HLCNHOTRS.

But the fact that such a combination was able to magnify distant objects was, although by no means understood, a very exciting discovery. It was considered “natural magic,” which added a certain measure of fantasy to the boldest speculations. The only problem with this lens combination was that they merely magnified objects, and did not offer a very clear image. It was impossible to see more than one could discern with the naked eye. In fact, for the most part, viewers armed with such a combination saw fewer details.

The important insight is that in the early sixteenth century, soon after

glassworkers began grinding lenses on both surfaces, and at the moment in which the optical quality could, in principle, be improved, the telescopic effect of a lens combination made with better spectacle glasses had been recognized. There were many different allusions to this effect in the literature of the sixteenth century, and it became so easily understood that we should no longer consider it to have been an exaggerated fantasy. After the second half of the sixteenth century, this effect became better known to scholars and to spectacle makers. The main reason that it was impossible to produce really clear images was due to the fact that in the early seventeenth century most of the spectacle lenses were still far below the quality needed. Furthermore, the complete lack of optical understanding of this strange effect prevented improvement.



The Events in Holland in the Autumn of 1608

THE EARLIEST MENTION concerning the invention of the telescope is found in a letter of the Committee of Councillors of the States of Zeeland in Middleburg to the Zeeland delegation at the States-General in The Hague. It was dated September 25, 1608.³⁶ The unnamed bearer of this letter was then recommended to Prince Maurice, Duke of Nassau. We read that the bearer claimed he was in the possession of an instrument that made it possible to see distant objects as if they were very close, and he further asserted that this was a completely new invention.

There is also an entry in the Minutes of the States-General from 2 October 1608³⁷ in which we read that a certain Hans Lipperhey, a native of Wesel, now a citizen of Middleburg and their chief spectacle maker, had invented an instrument that would allow one to see great distances. He requested that this invention remain a secret, and he asked for a privilege for thirty years (or a yearly pension), so that he would be able to make this instrument for the benefit of the country.

When Lipperhey arrived at The Hague, in the last days of September, a peace conference was coming to an end, and there was great excitement everywhere in the city. Nevertheless, Lipperhey's claims about his instrument were thought to be so important that a delegation of six representatives, from the six provinces, headed by Prince Maurice of Nassau and his half-brother Henry, stood ready to test the instrument carefully. They went with General Spinola, leader of the Spanish forces, to a tower in The Hague, one which had a panorama. The performance of the instrument made a very deep impression. The clock in the tower at Delft and the windows at the cathedral in Leiden could be seen very clearly. The impression

on General Spinola was so strong that he told Prince Maurice that from now on he would never feel safe in the field. Whereupon Prince Henry answered that in this case, he would forbid his troops to shoot at him.

This amusing story came down to us in a small news pamphlet entitled *Ambassades du Roy de Siam*. It was printed in October, in The Hague, with two second editions in Paris and Lyon.³⁸ Therefore Lipperhey had a good chance of getting the patent he had requested. In the following days there were many negotiations. Lipperhey was issued an order to make three binocular instruments within a year. His request for 1,000 guilders per instrument was considered exorbitant, and they finally came to terms at a total sum of 900 guilders. On the fifth of October Lipperhey was awarded 300 guilders as an advance payment, with the remaining 600 guilders to be turned over after the delivery and successful examination of the three binoculars. The decision about his pension was deferred until this point.

On October 15, the first binocular was successfully tested. Nevertheless, Lipperhey's request for a patent and for a pension was rejected, and he received instead a sum of 300 guilders, with a promise of the rest after the delivery of the two other instruments. What was the reason for this refusal, given that the instruments fully satisfied the examiners?

In the Minutes for October 14 we read that another young man, whose name is not recorded, made the claim that he, too, could make instruments to view distant objects. Today we are sure that this young man was none other than Zacharias Janssen, twenty years old and a spectacle maker in Middleburg.³⁹ And then, only a day later, in a letter written on October 15, a third person appeared, namely Jacob Andraenszoon of Alkmaar, also known by the Latinized name "Metius," requesting a patent for the exact same instrument. His instrument was examined, but its performance was not satisfactory. He was paid 100 guilders and was promised more if his next instrument was improved.

But the decision makers in The Hague were irritated by the emergence of three different people familiar with the principle of the invention in the course of only a few weeks. It was clear that it was impossible to keep the invention a secret, and that was the reason for their refusal of Lipperhey's request. The matter soon became even more complicated. In the *Mundus Jovialis* (Nuremberg, 1614), Simon Marius (1570–1624) described his first encounter with the new instrument. In 1608, during the Frankfurt autumn fair, Lord Johann Phillip Fuchs, privy councillor of Bimbach, met

a “Belgian” who claimed to be in the possession of an instrument with which it was possible to see distant objects more clearly. They discussed the matter, but Fuchs was not convinced. But when the “Belgian” brought the instrument to Fuchs for inspection, it was damaged, for the front lens was broken. One could nevertheless see that it did, in fact, magnify distant objects. But the price seemed much too high, and because the potential buyer could see how it was made, he refused it.

The Frankfurt autumn fair started on August 15 and ended on September 8. But at a later time it started in early September and went through the whole month.

From this story we must assume there were four people who knew of this secret. But critical investigations by Cornelis de Waard,⁴⁰ lead us to believe that this “Belgian” was none other than the aforementioned Zacharias Janssen. And the “instrument to see far” was only a telescopic system that had been well known for a long time.

We now confront the task of solving a rather difficult puzzle. It is astonishing that within a few decades of the first appearance of the telescope, nobody in Holland knew who its real inventor was. But this enigma also explains why, over the past four centuries, the story of the invention of the telescope is still very controversial, and is constantly discussed with new assumptions. Who, finally, received credit for the invention? Sometimes it is Metius, other times Janssen, and most often Lipperhey.⁴¹ Knowledge of the invention of the telescope spread very quickly through Germany and France and into Italy, and a short time later the first successful attempts were made in England.



The Breakthrough

NOW WE WILL SEE HOW this complicated story looks if we consider the investigation of the spectacle glasses discussed in chapter 7.

The oldest clear hint of a telescopic system dates back to Fracastoro in 1538. Then in the second half of the sixteenth century, more and more efforts were made to ameliorate the device, not only by increasing the magnification but also by improving the resolution. But none of these experiments was successful. We can be sure of this due to the fact that none of the attempts led anywhere and all of them quickly disappeared. The instrument associated with Bourne, moreover, though explained in great detail, cannot be found in any subsequent literature.

Until now, this situation was always explained by the suggestion that in the sixteenth century no one was aware of the potential and possibilities of such an instrument. But this assumption is strongly contradicted by the findings discussed in chapter 9. It was possible in the sixteenth century to recognize the magnifying effect of a system of two spectacle glasses of good quality. But such devices would not have been “telescopes” in the true sense of our definition (chapter 1). Their resolving powers were considerably worse than the resolution of the human eye. We have therefore termed them “telescopic systems” because they had exactly the same lens arrangement as the later real telescopes. But their lack of resolving power made it clear that a device, which only magnified a distant object without improving the visibility of details, was of no practical significance. These devices were sometimes looked upon as optical curiosities by scholars and spectacle makers, and led to continued experiments in the search for a solution.

But there were two even more important questions to be confronted in the second half of the sixteenth century.

1. How was it possible, that during the last eighty years of that century, the many attempts made to improve telescopic systems always ended in failure, and with no results other than blurry images? And how was this mysterious obstacle so suddenly surmounted by a spectacle maker in Holland?
2. More curiously, how was it possible, for other spectacle makers to duplicate this feat so quickly, when it would have been impossible only a few weeks earlier?

Recall the conclusions of the tests in chapter 7, where it was shown that spectacle glasses had not been improved in any way from the sixteenth century through the first decades of the seventeenth. Lipperhey, for his part, did not have better lenses than Bourne, Digges, or even Fracastoro. If Lipperhey's success had been due to an improved grinding technique, which he had developed years before, then neither his competitors, nor any of the other spectacle makers in Europe, would have been informed about it, and he alone would have received his patent, and could have made telescopes all on his own for many years.

But this problem can be more easily solved by the following assumption: Lipperhey, who had made his telescopic system with a fairly good spectacle glass in the front lens, made a very simple change. And the change was so simple that it was easily seen by anyone who looked at his telescope, especially by those who were familiar with such optical systems. And with this simple change it was possible to make an ordinary telescopic system into a real working telescope that gave clear images from distant objects.

To understand this change, we need to look at the Ronchi tests of the eight best spectacle glasses, which have already been discussed in chapter 7. In the best examples (figures 57 and 64), the Ronchi lines at the inner part of the lenses are parallel, and are comparable to the test image of the modern lens in figure 28A. The reason that these lenses do not form a perfectly clear image of the test plate (figure 44) is found in the much distorted Ronchi lines on the outer part of the lens. Here the amount of the distortion is many wavelengths. But if we put a paper diaphragm with

an aperture of 10 mm in front of these lenses, the result is that the optical influence of the distorted part of the lenses disappears, and the image becomes much clearer.

In figures 90 through 94 we see a dramatic change in the resolving power of these imperfect lenses, especially if we compare them with the telescope tests of these lenses in chapter 7. In the best-quality lenses, namely W07 (figure 90) and T09(2) (figure 92), the image is so much improved that the whole test plate, even the faintest last line, becomes very legible. Only T12(1) (figure 95) and W04L (figure 96), with their mediocre Ronchi test results, fail to show an improvement surpassing that of the human eye, for the last two lines remain unreadable.

This result will be surprising to anyone who is unfamiliar with optical theory. But of the 57 spectacle glasses tested, only five of them with the 10 mm diaphragm showed an improvement that would have surpassed the human eye. With four other lenses the improvement was in the ranges of the tests shown in figures 95 and 96. But the remaining 48 glasses were so poor in quality that even with the 10 mm diaphragm, the improvement remained nearly negligible.

All of this information makes it clear that the invention was only within the grasp of a spectacle maker who had a large stock of lenses for conducting these tedious experiments, and only to a spectacle maker who specialized in high-quality glasses. Scholars or even half scholars, like della Porta, had very few such opportunities.

How Lipperhey discovered this ingenious method of improvement in the image of a lens remains unknown. Nor do we know how the Venetian glassmaker thought up the idea of making lenses from blown-glass balls. Most likely it was due to conducting intelligent experiments along with a reasonable amount of creative intuition. The latter was and is today the real force behind every clever idea.

How Metius and Janssen learned of the simple modification Lipperhey used to make a successful instrument remains an enigma, and is material for further speculations. In World War II, during a bomb attack on Middleburg, the archives of the library were completely destroyed, and there is thus no way to obtain further insights from that source.

This simple but extremely effective change in a telescopic system spread quickly to France and then to Italy. To make a successful copy of the instrument, it was not even necessary to see it. Of course, we do not

Telescope tests of the seven best spectacle glasses from chapter 7 if the lens aperture is reduced by a diaphragm to 10 mm.

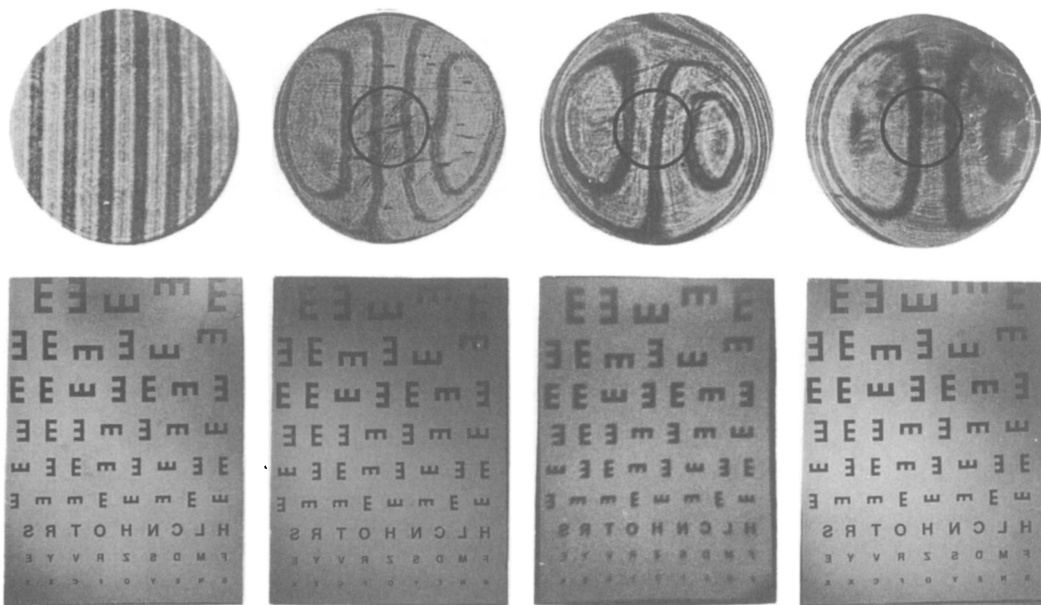


FIGURE 89.
Achromatic

FIGURE 90.
W07

FIGURE 9I.
Tog(I)

FIGURE 92.
TO9(2)

believe that all of the devices made by various lens-makers throughout Europe would have in every case resulted in a telescope. It is possible to get a clearer image by reducing the aperture, but only with fairly high-quality lenses would this improvement result in a real telescope. And we have already seen that the quality of the lenses in the early seventeenth century was very poor.

We can find this small diaphragm directly behind, or in front of the objective in all telescopes made during the first half of the seventeenth century that survived with the original optics. That configuration did not change before the middle of the century, when the Capuchin monk Schyrl de Rheita published *Oculus Enoch et Eliae* (1645), which included an improved polishing method for telescope objectives, a process he had developed with the Augsburg optician Johannes Wiesel. From that time the diameter of the objective diaphragm (called the telescope aperture)

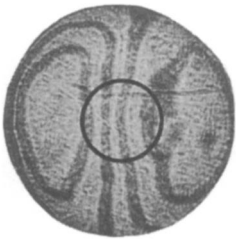


FIGURE 93.
BHOI (L)



FIGURE 94.
BHOI (R)

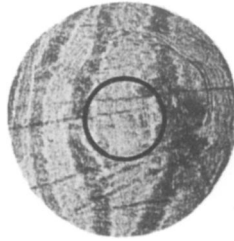
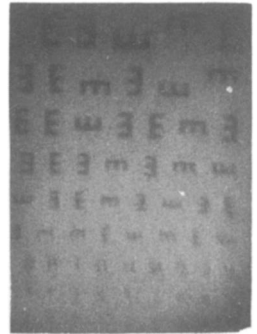
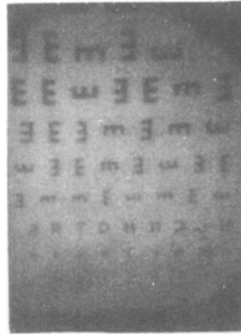
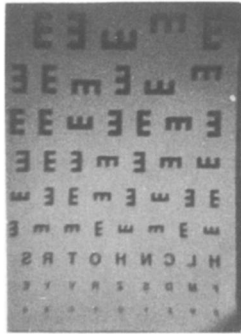
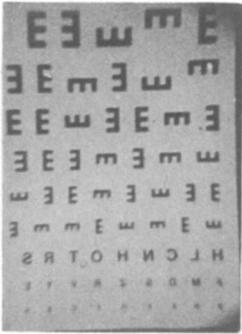


FIGURE 95.
T12(I)



FIGURE 96.
WO4L



could be remarkably enlarged. Nevertheless the chromatic aberration of the single lens objective still required reduction by a diaphragm.

The first person who conducted scholarly experiments concerning lens quality and diaphragm aperture was Galileo Galilei, and from him we learn how extremely difficult it was to obtain, even from skilled spectacle makers, lenses of the requisite quality. The first person who succeeded in explaining the marvelous effect of this new instrument was Johannes Kepler. In his *Dioptrice* (1611), he laid the scientific base for the unprecedented development of the telescope up until present time.



Who Is the Inventor of the Telescope?

EVEN AFTER THIS LONG WALK through many centuries, there still remains one last important question: Who receives credit as the true inventor of the telescope?

Based on modern legal conceptions, there is no doubt that it is Lipperhey. He was clearly the first inventor who convincingly demonstrated a real instrument. There is no evidence that Janssen had actually manufactured a real telescope to back up his claim that he could make one. In the minutes his name is not mentioned, and there is no indication that a sum was paid to him. Therefore we can assume the device he demonstrated on October 14 in The Hague did not convince the examiners, and was probably the one with the broken front lens which he had already shown to Fuchs von Bimbach at the Frankfurt autumn fair in September.

Nor was Metius able to make an instrument of sufficient quality, and the examiners recommended that he improve it because it did not perform as well as Lipperhey's telescope. Both instruments seem to have been simple telescopic systems, with insufficient resolution, that had already been well known for many decades. Lipperhey received the order to make three sets of binoculars, or six telescopes. A binocular is a difficult arrangement of two telescopes of almost exact optical magnification and centering, for otherwise it would be impossible to look through the instrument. Lipperhey needed, therefore, to make pairs of lenses of exactly the same focal length with sufficient optical quality. Every one of his three binoculars convinced and satisfied the examiners, who would not have given him the promised money without such results. There is thus no doubt that Lip-

perhey had understood and mastered the technical difficulties and conditions that had to be fulfilled to create a successful telescope.

It is not impossible to believe that in the sixteenth century someone could have made a working telescope without using a diaphragm. Such an arrangement could have worked, in principle, with a high-quality front lens, provided the lens diameter was small enough. We already know that making fairly good lenses was possible in the early sixteenth century, but because the maker did not understand the real reason of his success he could not repeat it. It remained an irreproducible exception. Therefore he can never receive the honor of being the inventor of the telescope. An inventor of a device must have the exact knowledge, not just of the scientific method of its working, but of all the important principles of its making.

There is no doubt that Lipperhey was the first who had this knowledge. He could repeat the construction of the telescope as often as needed, including binoculars, the most difficult construction. His idea was as simple as ingenious, but this simplicity should not diminish its merits. We can see how his success was based on numerous small steps made over many centuries. He just happened to be the last link in a long chain.

Today such questions are not of great importance. The merit that Lipperhey earned by his crucial contribution to the construction of the telescope cannot be taken away from him by anyone. The development of this instrument has enriched our cultural knowledge over the course of four centuries in an amount that was impossible to foresee in his time.



The Most Important Stations on the Route to the Invention of the Telescope

Antiquity

The first mechanical grinding method with a rotating plane plate emerged. Artisans ground rock-crystal with emery, and polished it with red iron oxide (later called tripolitanian color), to create high-quality crystal lenses. This discovery made the construction of so-called “magnifying stones” possible.

Early Middle Ages

In the ninth century, during the “Carolingian Renaissance,” the Middle Eastern art of stone grinding spread into the monastery workshops of the entire Frankish Empire which included France, Germany, Switzerland, and Italy.

High Middle Ages

The art of stone grinding developed in monasteries to its highest perfection over these centuries. Often the surfaces were of such regularity that they could only be the result of many years of practice.

The time of the Crusades (twelfth and thirteenth centuries)

The large number of relics imported to Europe by the Crusaders required a completely new mode of presentation. That was the beginning of the

grinding of large rock-crystal windows to protect the relics enshrined behind them. These windows were often carefully ground weak plano-convex lenses.

It is very probable that highly skilled monks quickly realized that many of these crystal lenses had the ability to completely correct the “weak vision” of their older presbyopic confreres. This dioptrical vision aid was made only in the monasterys’ stone-grinding workshops. The oldest depiction of such a vision aid is found in the cathedral of Constance. It dates from 1260.

The most important consequence of this discovery was the insight that the “weakness of old eyes” was not a medical problem, but could be completely remedied by optical means.

The invention of *cristallum* in Venice (about 1280)

After the end of the Crusades, when commercial contact with the Middle East was again possible, the Venetians learned of a new material in Egypt called *natrun*. They found that when it was added to quartz sand, the properties of the melt were much superior to that where potash was used. The glass was much clearer, with fewer bubbles and with only a faint color.

In 1284, soon after this discovery, the High Court of Venice enacted a trade regulation with the stipulation that all high-quality glassware was to be made only with the newly invented clear and white glass called *cristallum*.

The invention of spectacles in Venice (about 1285)

Two very important conditions were now realized:

1. The shape of the lenses to correct presbyopia was known, and
2. With the discovery of *cristallum*, artisans now had material appropriate for the manufacture of such dioptrical vision aids, and it was much easier to work with *cristallum* than with hard rock-crystal.

Together with these two independent inventions, the stone-grinding monks and the Venetian *cristalleri* discovered that the required lenses

could be made much more easily by blowing spheres of *cristallum* and cutting discs from them. This meant that it was only necessary to grind the concave surfaces to obtain a number of similar small lenses that could then be worn in pairs in front of the eyes. With this idea spectacles were invented. The first mention of *roidi da ogli* was in supplements to the trade regulations, dated April 2, in the year 1300. A significant disadvantage to this method was the fact that it was very difficult to produce spheres with enough regularity for high-precision lenses. All the lenses made by this technique have been found to be seriously astigmatic.

Negative lenses for myopic eyes made in the sphere-blowing technique

Because one had to grind the concave inner surfaces of the discs in order to help presbyopic eyes, it was easy to see that myopic eyes required lens-makers to grind the outer convex surfaces. The manufacture of negative lenses was therefore just as easy as that of positive ones. From the beginning, in the late thirteenth century, negative lenses for myopics have been made with even higher power than the positive ones.

The invention of lens grinding in concave molds

The invention of printed books with movable type led to a rapid spread in the art of reading. And because the first readers were probably of an older generation, an increased demand for spectacle glasses quickly emerged. Venice and northern Italy were soon unable to meet this growing demand.

In 1478, the first lens-maker settled in Nuremberg. By the end of the century eleven more such artisans were working in that city, but none of the spectacles manufactured in Nuremberg were made by the traditional Italian sphere-blowing technique. Instead, a round disc was cut from plane window glass, and the convex surface was made by grinding in a concave mold. The advantage of this invention was the possibility (at least in principle), of making a great improvement in the sphericity of the convex shape, and therefore in the quality of the spectacles. But soon the demand for spectacles grew so great, that they became a mass-produced item of low cost, and with some drop in quality. Examination of many

spectacles from this period makes it quite clear that a mere 10 percent of the glasses were of good quality.

Negative lenses by the mold-grinding technique

These lenses were made by grinding plane discs on the surface of iron cannon balls. They were ground only on one surface, while the other side remained flat. Because of this, spheres became available in diameters ranging from a few centimeters to approximately 25 cm, and the dioptric powers were fairly high. But this was also a requirement of the wearers.

The discovery of the magnifying effect of convenient combinations of two lenses

Already in the early sixteenth century, all of the components necessary to make a telescope were available. Scholars of that era soon discovered the magnifying effect of two suitable lenses for distant objects. Unfortunately this effect was not easy to discover because it required lenses of at least mediocre quality. But we do find different reports of this observation in the literature of the sixteenth century.

The invention of the telescope

Toward the end of the sixteenth century, knowledge of this magnifying effect became available to all scholars and to many spectacle makers. There were several very serious attempts, although none met with success, to improve the visibility of faint details over what could be seen with the unassisted eye. The phenomenon itself, however, remained completely misunderstood. In 1608, Johannes Lipperhey, a lens-maker in Middleburg, was the first to succeed in improving the resolving power of a telescopic system by putting a diaphragm with small aperture in front of the main lens. This simple idea was the birth of the telescope.

Because of the simplicity of the improvement, the knowledge spread very quickly to many spectacle makers throughout Europe. But we can also assume that most of the devices made in these early years were not real telescopes, because lenses of requisite quality would not have been readily available.



Acknowledgments

THIS BOOK, WHICH REQUIRED several years of research, would not have been possible without the generous help of many people.

The most important keys, which opened doors to unknown paths, and which finally led to the definite solution, were the rivet spectacles from Wienhausen and the table reliquary in Halberstadt. Mrs. Renate von Randow, abbess of the lady abbey Wienhausen, gave me generous support and confidence during the difficult investigation of the 700-year-old spectacle glasses. In the same gracious manner, Mrs. Barbara Möhring, abbess of the monastery in Isenhagen, arranged access to the rivet spectacles found and preserved in this monastery.

Another important colleague was Mr. Wolfgang Brandis, the librarian in the monastery Wienhausen. I had many fruitful discussions with him and he gave me a very important hint concerning the plate-reliquary in the cathedral of Halberstadt. This discovery opened the door that explained how the first "vision aids" were made in the monasteries 800 years ago, followed by the invention of spectacles in Venice 100 years later.

Mr. Jörg Richter, curator at the cathedral of Halberstadt, understood my request and gave all of the necessary orders so that I could investigate this precious work of art.

Dr. Silke Ackermann, curator at the British Museum in London, helped me to take all of the detailed measurements on the Nimrud Lens and also on the Lothar Crystal, two incomparably precious medieval artworks.

The Gothic book-case with the four spectacle glasses painted on the underside, preserved in the museum of the principality of Lüneburg, formed the end of my measurements of fourteenth-century lenses. Museum director Dr. Michael allowed me to undertake detailed examinations of this unique medieval masterpiece.

When we finally finished all of these detailed investigations it was possible to reveal the secret of the evolution and invention of the spectacle in

Acknowledgments

the late thirteenth century. But this new knowledge was only the foundation. It still was insufficient to understand the development of the telescope, which appeared 300 years later.

In Wienhausen researchers found spectacles that dated back to the early sixteenth century. Therefore these spectacles are the missing link, the necessary connection between the rivet spectacle and the evolution of the lens in the late Middle Ages. But there are other preserved spectacles from the sixteenth century in private collections and museums.

Most importantly, I give thanks to my friend Udo Timm, and his unique collection, which grew over many decades due to his great knowledge of this subject. It was a treasure trove for sixteenth and seventeenth-century spectacles.

No less important is the evidence found from the very fine collection of spectacles from Ingrid and Werner Weismüller.

Also, the spectacles originally belonging to the Nuremberg humanist Willibald Pirkheimer gave important insights, although optical measurements were impossible because of their complete devitrification. I received much help in my investigations from Mrs. Krauss, curator of the Wartburg museum, where the spectacles are now preserved.

Dr. Jane Wess, curator of the Astronomy Department of the Science Museum in London, and Mr. Hans Hooimajers, curator at the Museum Boerhaave in Leiden, gave me a generous amount of help during the investigations of the sixteenth-century glasses, at their respective museums.

And let me not forget the time-consuming reading of the text, and translation into English, that was done with great care by my friends Professors Rudd and Jaecks in Lincoln, Nebraska.

And last but certainly not least, I have to thank my wife who, though she denies any credit, had her decisive share in the success of the final result.

The reader, who was not involved in the background and evolution of this monograph, could believe that all of these finds are only the work of the author. But this would be completely wrong. The intention and the enthusiasm of all these people, those not mentioned in this book, helped me uncover this 400-year-old enigma and is one of the most important reasons I finally succeeded in finding the answers. Without their help, it would have been impossible to reach any goal. Their personal commitment and their confidence in me deserve my most heartfelt thanks.



1. Bonaini, F. (1845). Published the chronicle of Sta. Catharina at Pisa. *Archivio storico italiano*, Vol. 6, part 2, pp. 397–593.
2. Rosen, E. (January, 1956). The invention of eyeglasses. *Journal of the History of Medicine*, p. 13.
3. Ibid., p. 14.
4. Kepler, J. (1604). Ad vitellionem paralipomena. Deutsch in F. Plehn, *Ostwalds Klassiker* Nr. 198.
5. Gasson, W. (December, 1972). The oldest lens in the world. *The Ophthalmic Optician*.
6. O.B.S.E. (April 15, 1938). The layard lens. *The Optician*.
7. Kohlhaussen, H. (1969). *Europäisches Kunsthandwerk, Vorromanik und Romanik Umschau Verlag, Frankfurt / Main*, S. XXII und S. 18.
8. Ahlström, O. (May 19, 1950). Swedish Vikings and optical lenses. *The Optician*.
9. Lingelbach, B., and Schmidt, O. (2002). Aspärische Linsen aus dem 11. Jahrhundert. *Zeitschrift f. prakt. Augenheilkunde*, 23, S. 397–406.
10. Ibid. The Visby-Lenses, OSA Annual Meeting, Baltimore, MD, October 4–9, 1998.
11. Brommer, H., and Frey, E. (2005). *Das Konstanzer Münster*. Schnell + Steiner, Regensburg, 2. Aufl.
12. Dreier, F. A. (1989). Venezianische Gläser. *Katalog des Kunstgewerbemuseums*. Berlin. Vol. XII, p. 13.
13. Greeff, R. (1922). Eine venetianische Brillenmacherordnung aus den Jahren 1284–1317. *Deutsche optische Wochenschrift*, Jg. VIII.
14. Matson, F. R. (1951). The composition and working properties of ancient glasses. *Journal of Chemical Education*, Vol. 28, pp. 82–85.
15. Appuhn, H. (1958). Ein denkwürdiger Fund. *Zeiss Werkzeitschrift*, Heft 27, S. 1–8.
16. von Pflugk, A. (1927). Beiträge zur Geschichte der Brille aus alten Abbildungen *Zeitschr. f. opht. Optik* Bd. 14, S. 138–145.
17. Ibid. (1927). Über Brillen in alter Kirchenkunst. *Zeitschr. f. opht. Opti*, Bd. 31, S. 34–37.

18. Appuhn, H. (März 1963). Hinterglasmalereien auf den ältesten Brillengläsern *Werkzeitschr. Schott & Gen. Jenaer Glas. Mainz, März, S. 12–16.*
19. Willach, R. (March, 2001). The development of lens grinding and polishing techniques in the first half of the 17th century. *SIS Bulletin*, No. 68.
20. Strobl, S. (1990). Glastechnik des Mittelalters. Gentner Verlag. *Aus der Schedula des Theophilus*, S. 57 und S. 84.
21. Ilardi, V. (1976). Eyeglasses and concave lenses in 15th century Florence and Milan. *Renaissance Quarterly*, Vol. 29, No. 3, pp. 341–360.
22. Ronchi, V. (1942/1964). *Galileo e il Cannocchiale*. Udine and Turin.
23. Lindberg, D. C., Steneck, N. H., (1972). The sense of vision and the origins of modern science. *Science, medicine and society in the Renaissance*, New York, p. 29.
24. von Pflugk, A. Die Ordnungen der Nürnberger Brillenmacher. *Forsch. z. Gesch. d. Optik*, Bd. 1, S. 203–222.
25. ZVA. *450 Jahre im Dienste des Sehens*. Herausgeber: Zentralverband der Augenoptiker, S. 15.
26. Neuburger, S. (1904). Die Regensburger Brillenmacherordnung. Janus, Harlem, S. 94–102.
27. Nürnberger “Parillenmacherordnung”, Bayerisches Staatsarchiv, Nürnberg.
28. Müller, C. (1921). Das Original der Regensburger Brillenmacherordnung. *Zeitschr. f. opht. Optik*, Bd. 9, S. 129–130.
29. von Pflugk, A. (1923). Noch eine alte deutsche Brillenmacherordnung. *Zeitschr. f. opht. Optik*, Bd. 11, S. 33–40.
30. Hieronimus Sirturus. (1618). *Telescopium: sive ars perficiendi*. Frankfurt CAPVT III, “De hodierna huius artis corruptela.”
31. ZVA. *450 Jahre im Dienste des Sehens*, S. 25.
32. Hieronimus Sirturus. *Telescopium*. CAPUT XV, “Globulus ferreus quomodo aptandus operi.”
33. van Helden, A. (June, 1977). The invention of the telescope. *Journal of the American Philosophical Society*, pp. 28–47.
34. Rosen, E. (1954). Did Roger Bacon invent eyeglasses? *Archiv International d'Histoire des Sciences*, No. 26, pp. 3–15.
35. Dupré, S. (2008). *The Making of Practical Optics: Mathematical Practitioners and the Transformation of Natural Knowledge in Early Modern Europe*. Cormack Lesley (Ed.).
36. van Helden, A. *The invention of the telescope*, p. 35.
37. *Ibid.*, p. 36.
38. *Ambassades du Roy de Siam en Voyage à l'excellence du Prince Maurice, arrivé a la Haye le 10 September 1608*. Reprint by Drake Stillman, (1976).

Notes

The unsung journalist and the origin of the telescope. Zeitlin u. Ver Brugge, Los Angeles.

39. van Helden, A. *The invention of the telescope*, pp. 38–39.

40. Waard, C. (1906). *De uitvinding der Verrekijkers*, p. 174. S. Gravenhage.

41. van Helden, A. (1975). The historical problem of the invention of the telescope. *History of Science*, S. 251–263.



Further Reading

Ilardi, V. (2007). *Renaissance Vision from Spectacles to Telescopes*. American Philosophical Society, Philadelphia.

Riekher R. (1990). *Fernrohre und ihre Meister*. 2. Auflage 1990, VEB Verlag Technik, Berlin.

CHAPTER 2

Beck, H. C. (1928). Early magnifying glasses. *Antiquarian Journal* 8, pp. 327–330.

Enoch, J. M. (1998). The enigma of early lens use. What is a lens? How do we know that an apparent lens was used as a lens? *Technology and Culture* 39, pp. 273–291.

Enoch, J. M. (1999). First lenses originated in Egypt about 4,600 years ago. *Documenta Ophthalmologia* 99, pp. 303–314.

Euclid. (1945). *The Optics of Euclid*, translated by Harry Edward Burton. *Journal of the Optical Society of America* 35, pp. 357–372.

Meyerhof, M. (1920). Die Optik der Araber. *Zeitschr. f. opht. Optik*, Jg. 8, S. 16–29, 42–54, 86–90.

Risner, F. (1572). *Opticae Thesaurus, Alhazeni Arabis libri septem . . .* Basel.

Sakellarakis, Y., and Sines, G. (1987). Lenses in antiquity. *American Journal of Archaeology* 91, pp. 191–196.

Wiedemann, E. (1884). Über den Apparat zur Untersuchung der Brechung des Lichts von Ibn Al Haitam. *Annalen der Physik und Chemie*, Bd. 21, S. 541–544.

CHAPTER 3

Greeff, R. (1923). Der Beril des mittelhochdeutschen Dichters Albrecht (1270). *Zeitschr. f. opht. Optik*, Bd. 11, S. 66–67.

Greeff, R. (1923). Der vergrößernde Kristall des Konrad von Würzburg (1275). *Zeitschr. f. opht. Optik*, Bd. 11, S. 98–101.

CHAPTER 5

Gibbs, R. (1989). Thomaso da Modena. *Cambridge University Press*, New York.

Further Reading

- Herzog, August. Bibliothek Wolfenbüttel, Cod. Guelf 69. Österreichische Nationalbibliothek, Cod. 2527.
Theophilus p. "De diversis artibus" oder "Schedula diversarum artium."

CHAPTER 6

- Albertotti, G. (1914). Note critiche e bibliografiche riguardanti la storia degli occhiali. Estratto degli Annali di Ottalmologia. Anno XLIII, fasc. 3 u. 4, Pavia.
- Appuhn, H. (Okt. 1958). Wie alt sind die Nietbrillen von Wienhausen? *Carl Zeiss Werkzeitschrift*, S. 62–65.
- Greeff, R. (1917). Nikolaus von Cusas Buch "De Beryllo." *Zeitschr. f. opht. Optik*, Bd. V, S. 42–44.
- Greeff, R. (1917). Die Veglia des Carlo Dati über die Erfindung der Brillen. *Zeitschr. f. opht. Optik*, Bd. V, S. 65–77.
- Greeff, R. (1918). Die Briefe des Francesco Redi über die Erfindung der Brillen. *Zeitschr. f. opht. Optik*, Bd. VI, S. 2–11.
- Greeff, R. (1921). Die Erfindung der Augengläser. Verlag Alexander Ehrlich, *Optische Bücherei*, Bd. 1.
- Greeff, R. (1924). Frühe Sehhilfen. *Zeitschr. f. opht. Optik*, Bd. 12, S. 1–2.
- Greeff, R. (1924). Zwei frühe niederländische Brillennachweise. *Zeitschr. f. opht. Optik*, Bd. 12, S. 33.
- Ilardi, V. (2001). The role of Florence in the development and commerce of spectacles. Special Symposium Issue of the Renaissance Society of America. Edited by Vincent Ilardi and Laura Ronchi. *Atti della Fondazione Giorgio Ronchi*, 56(1), pp. 163–176.
- Rhodes, M. (1982). A Pair of Fifteenth-Century Spectacle Frames in the City of London. *Antiquarian Journal* 52, pp. 57–73.
- Rohr, M. (1937). Gedanken zur Geschichte der Brillenherstellung. *Forsch. z. Gesch. d. Optik*, Bd. 2, 2. Heft, S. 121–138.
- Rosen, E. (Jan. 1956). The invention of eyeglasses. *Journal of the History of Medicine*, pp. 13–218.
- Rosen, E. (1953). Carlo Dati and the Invention of Eyeglasses. *ISIS* 44, pp. 4–5.
- Steuer, H. (1985). Mittelalterliche Nietbrillen aus Freiburg im Breisgau. *Archaeologische Nachrichten aus Baden*, 34.

CHAPTER 7

- Enoch, J. M. (2001). Concave mirrors used for visual corrections during the Renaissance and earlier. *Special Symposium Issue of the Renaissance Society of America*, 56(1), pp. 133–148.
- Fehring, G. P. (1974). Fundberichte aus Baden-Württemberg 1, S. 665–671. Mittelalterliche Funde aus St. Petrus und Paulus in Böttingen, Gem. Darmstadt. (Possibly oldest Nuremberg wire spectacle.)

Further Reading

- Greeff, R. (1918). Daza de Valdes: Uso de los Antochos 1623. *Zeitschr. f. opht. Optik*, Bd. 6, S. 97–104.
- Pflugk, A. (1932). Ein Beitrag zur Geschichte des Wettbewerbes der Nürnberger und Regensburger Brillenmacher um das Jahr 1600. *Zeitschr. f. opht. Optik*, Bd. 20, S. 164–169.
- Rohr, M. (1922). Ein Versuch zur Ermittlung der optischen Kenntnisse der Brillenhersteller um das Jahr 1600. *Zeitschr. f. opht. Optik*, Bd. 10, S. 1–8.
- Rohr, M. (1931). Unser Wissen von den Nürnberger und Fürther Brillenmachern. *Zeitschr. f. opht. Optik*, Bd. 19, S. 33–58.
- von Pflugk, A. (1928). Lederbrillen. *Zeitschr. f. opht. Optik*, Bd. 16, S. 2–10.
- von Pflugk, A. (1942). Ein Beitrag zu unseren Kenntnissen der Meisterstücke der Alten Brillenmacher. *Zeitschr. f. opht. Optik*, Bd. 30, S. 16–21.

CHAPTER 9

- Bacon, R. (1897). *Opus majus*. Edited by J. H. Bridges, Oxford, quoted in 33, p. 28.
- da Vinci, L. *Tagebücher und Aufzeichnungen*. Translated and edited by Lücke Theodor in 1953. Leipzig, Paul List Verlag.
- della Porta, G. B. (1589). *Magia naturalis*, libri XX, libri XVII, Cap. 10, Naples, quoted in 33, pp. 34, 44.
- Gualterotti, R. (1605). Scherzi degli spirite animali dettati con l'occasione de l'oscurazione de l'anno, quoted in 33, pp. 35, 45.
- Ronan, C., & Turner, G. L'E. (1993). Was there an Elizabethan Telescope? *Bulletin of the Scientific Society*, No. 37, pp. 2–10.

CHAPTER 10

- Hensen, A. H. L. (1923). De Verrekijkers van Prinz Maurits en van Aartshertog Albertus. *Medeelingen van het Nederlantsch Historisch Instituut de Rome*, pp. 199–204.
- Sluiter, E. (August, 1997). The telescope before Galileo. *Journal for the History of Astronomy*, pp. 223–234.

CHAPTER 11

- Borel, P. (1655). De vero telescopii inventore, quoted in 33, p. 58.
- Galilei, Galileo. (1610). *Sidereus Nuncius*, Venice. In Anna Mudry (ed.), *Galileo Galilei, Schriften, Briefe, Dokumente*, Vol. 1. (German translation, 1987).
- Kepler, J. (1611). *Dioptrice*, Augsburg. German translation in *Ostwalds Klassiker*, No 144.
- Marius, S. (1614). *Mundus Jovialis*, Nürnberg. In Schlör Joachim (ed.), *Fränkische Geschichte*. (German translation, 1988).
- Pedersen, O. (1968). Sagredo's Optical Research, *Centaurus* 13, pp. 139–150.



About the Author

ROLF WILLACH studied physics, mathematics, and astronomy at the Universities of Bern (Switzerland) and Göttingen (Germany). After several years as Assistant Professor of Physics at the Institute of Astronomy in Bern, he is now self-employed in the development of electronic and optical sensor techniques.

For twenty years he has had a special interest in researching the history of the development of optics, particularly the telescope, and has published articles about his findings in numerous journals.

Other Articles by Rolf Willach

Die Erfindung des achromatischen Fernrohrobjektivs. *Sterne und Weltraum* (1991), Teil 1, Heft 3, S. 167–173; Teil 2, Heft 5, S. 290–295.

Schyrl de Rheita und die Verbesserung des Linsenfernrohres in der Mitte des 17. Jahrhunderts. *Sterne und Weltraum* (1995), Teil 1, Heft 2, S. 102–110; Teil 2, Heft 3, S. 186–192.

New Light on the Invention of the Achromatic Telescope Objective. *Notes and Records of the Royal Society*, London, 50:2 (1996), pp. 195–210.

The Early History of the Achromatic Objective. *Journal of the Antique Telescope Society* 12 (1997), pp. 4–13.

The Development of Lens Grinding and Polishing Techniques in the First Half of the 17th Century. *Bulletin of the Scientific Instrument Society*, London, 68 (2001), pp. 10–15.

The Development of Telescope Optics in the Middle of the Seventeenth Century. *Annals of Science* 58 (2001), pp. 381–398.

James Short and the Development of the Reflecting Telescope. *Journal of the Antique Telescope Society* 20 (2001), pp. 3–18.

The Wiesel Telescopes in the Castle of Skokloster and their Historical Background. *Bulletin of the Scientific Instrument Society*, London, 73 (2002), pp. 17–22.

The Heliometer. Instrument for Gauging Distances in Space. *Journal of the Antique Telescope Society*, Vol. 26 (2004), pp. 5–16.

The Development of the Reflecting Telescope in the 18th Century from John Hadley to James Short. *Atti della Fondazione Giorgio Ronchi*, Firenze, 62 (March–April 2007), pp. 255–288.

♦ ♦ ♦



After the telescope became known in 1608–1609, a number of people in widely separate locations claimed that they had such a device long before the announcement came from The Hague; in the summer of 1608, no one had a telescope, in the summer of 1609, everyone had one.

For a number of years Rolf Willach has quietly tested early spectacle lenses in museums and private collections, and now he reports on this

study, which gives an entirely new explanation of the invention of the telescope and solves the conundrum mentioned above. It leaves a smaller question at the end, but I will not give the plot away. Read and enjoy.

—ALBERT VAN HELDEN

author of *The Invention of the Telescope*

(Transactions of the American Philosophical Society, volume 67, part 4)



ROLF WILLACH is an optical engineer and independent scholar who worked for several years in the Department of Physics at the Institute of Astronomy in Bern. He has written extensively on the history of the development of optics and the telescope.



Transactions of the American Philosophical Society
held at Philadelphia for promoting useful knowledge,
volume 98, part 5

\$35.00

ISBN 978-1-60618-985-6

5 3 5 0 0 >



9 781606 189856